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Ionization and Photo-Electric Properties of Vapors of Alkali Metals

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IONIZATION AND PHOTO-ELECTRIC PROPERTIES OF VAPORS OF ALKALI METALS

BY

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Samuel Herbert Anderson

ENTITLED "Ionization and Photo-Electric Properties of Vapors of Alkali Metals."

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Doctor of Philosophy in Physics.

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IONIZATION AND PHOTO-ELECTRIC PROPERTIES OF VAPORS OF ALKALI METALS.

Introduction.

It is a well recognized fact that the photo-electric effect may give some definite information of the nature of radiation and of the distribution of energy in light waves. The importance of this phenomenon makes it very desirable to have reliable quantitative data of the relation between the incident wave length illuminating a metal and the positive potential assumed under such conditions. So far the results of different observers show great discrepancies. E. Ladenburg[1], working in the region $\lambda 2700$ to $\lambda 2000$, obtained data which, according to his interpretation, show that the relation is a linear one and a verification of Plank's theory of radiation which may be expressed by

$$P = \frac{k_1}{e} n$$

where P is the potential, e the elementary electrical charge, k_1 a constant, and n the frequency of the incident light. Hull[2], working in the region $\lambda 1710$ to $\lambda 1230$ obtained data which he interprets in the same way. While Kunz[3], working over a range of $\lambda 5000$ to $\lambda 2000$ obtained data which verify his theory of radiation[4] which may be expressed by

$$P = \frac{k_2}{e} n^2$$

That is, the potential which the illuminated metal assumes varies as the square of the frequency and not directly as the frequency. More recently Wright[5] has obtained curves for the relation between

1 Phys. Zeits., VIII, p.590, 1907.
2 Am. Jr. of Sc., 28, p.251, 1909.
3 Phys. Rev., 33, p.208, 1911
4 Phys.Rev., 29, p.212, 1909.
5 Phys.Rev., 33, p.43, 1911.

the wave length and positive potential which differ both from the results of Ladenburg and Hull and of Kunz, and might indicate that the phenomenon is of a resonance nature which would be in accord with neither Plank's nor Kunz's theory.

Furthermore, the work of Millikan[1] and Wright (l.c.) shows that the magnitude of the photo-electric effect is largely determined by surface conditions. Gehrts[2] has shown that reflection of electrons and secondary electrons may produce effects which amount to 40 or 50 per cent of the original effects; and consequently the methods of investigation must be such as to avoid these. Hughes[3] has shown that metal surfaces procured by distillation of the metals in vacuo give a larger photo-electric potential than obtained from polished surfaces; and while smaller than the potential obtained after the metal had been made the cathode in a glow discharge, much more stable and constant. The work of all these observers shows that the photo-electric effect is far from a simple one. The exact law can not be known until all the factors entering in are known and understood.

In the Physical Laboratory of the University of Illinois considerable work has been done upon the photo-electric effect of alkali metals. The advantages of working with these metals are: (1) a clean surface can easily be obtained by distillation in vacuo, and (2) these metals give larger photo-electric currents than other metals. In investigations carried out by Dr. J. Kunz, J.G. Kemp and the author, it has been observed that there is present in tubes prepared as photo-electric cells, containing alkali metals, a conduction due to something else than the electron current arising from

1 Phys. Rev.,34, p. 68, 1912
2 Ann. der Phys. 36, p.995, 1911
3 Proc. Camb. Phil. Soc. 16, p. 167.

the photo-electric action. It was thought that probably this was due to ionization of the vapor of the alkali metals. Therefore the following investigation was undertaken to determine (1) whether or not there was a spontaneous ionization of the vapors of alkali metals and (2) to determine the magnitude of the currents of conduction for different temperatures.

Füchtbauer[1] has made some investigation of the spontaneous ionization of sodium vapor at temperatures ranging from 190°C. to 330°C. The object of his investigation was to find the relation between the ionization of the vapor and the absorption of its line spectra. He observed an absorption of the D lines when the temperature of the vapor reached 190°, and hence began the investigation of ionization at this temperature. In a later paper[2] he gives some results obtained with caesium vapor, but in an atmosphere of helium of 196 mm. pressure, which would render the results quite different from those obtained with caesium vapor alone. The temperatures he used for caesium were from 150°C. to 210°C. In the former paper he gives a curve of conduction in sodium vapor which has very little of the characteristics features of an ionization curve. In the latter paper ccurves are shown which do approximate ionization curves.

Fredenhagen[3] in an investigation on the electrons given off from sodium and potassium made some observation of the conductivity of the vapors of these metals. He heated the potassium vapor up to 420° and the sodium to 500° and found no currents that were measurable with a galvanometer that gave a deflection of one millimeter for a current of 3.7×10^{-10} amperes. The tube used for this part of his work was of the same type as used by the author, see plate I, fig.1.

1 Phys. Zeits. 10, p.374, 1909
2 Phys. Zeits. 12, p.225, 1911
3 Phys. Zeits. 12, p.398, 1911

The investigations of Füchtbauer and Fredenhagen do not throw much light on the Photo-electric phenomenon. One cannot tell whether the conductivity they obtained is due to the vapor alone, or to particles which are given off from the metal which was present in the tube containing the electrodes. And it is especially desirable to know whether or not there is a spontaneous ionization at ordinary temperatures, 20° to 25°C.

Experimental Method.

Two types of tubes were used in this investigation. In the first, plate I, fig. 1, page 5, the two electrodes, a and b were of the same material, viz., nickel, and of the same dimensions. In the second, plate I, fig, 2, one electrode, b, consisted of the alkali metal, potassium or caesium; the other, a, was a disk of nickel. The conductivity thru the alkali vapor was measured in the following manner: one terminal of a battery was applied to one electrode, the other terminal being grounded; the other electrode was kept at zero potential and the current flowing through the tube was measured. The electrode which was connected to the battery was a, (figs, 1 and 2), in each case. Whenever it is said, "a positive potential was applied to the tube", we mean that the electrode a was connected to the positive terminal of the battery. The current was measured in one of three ways, depending upon the magnitude; (1) for currents of the order 10^{-13} to 10^{-11} amperes, electrode a of the tube was joined to one pair of quadrants of a Dolezalek electrometer and the rate of deflection of the electrometer needle was observed; (2) for currents of the order 10^{-11} to 10^{-9} amperes, electrode a was grounded through a high resistance and the fall of potential across the resistance measured with the electrometer; (3) for currents of the

Plate I

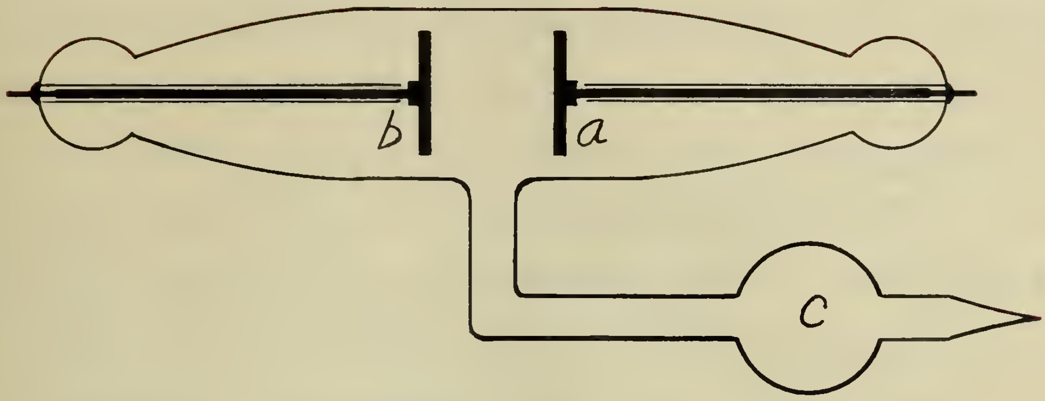


Fig. 1.

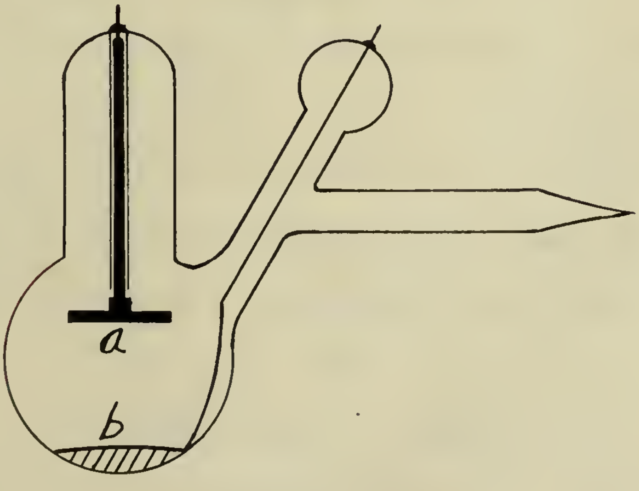


Fig. 2.

order 10^{-9} and greater a galvanometer was used.

In using the tube of the first type potassium was placed in bulb c, (fig. 1), and a series of measurements taken for both positive and negative potentials for the temperatures 25°, 50° and 100° with the tube in darkness. Then the potassium was poured into the main tube and lodged between the electrodes, but not in contact with either of them, and a series of measurements taken for 25°, 50° and 100° and 150° with the tube in darkness and also with a beam of light falling on the potassium, but not on the electrodes.

With the tube of the second type, (fig. 2), a series was taken with potassium for one electrode for 25°, 50°, 100° and 150°, both in darkness and with the potassium illuminated. The fourth series of measurements were taken with the tube of the second type with caesium for one electrode for temperatures of 25°, 40°, 70° and 100°.

Experimental Details.

Construction and Preparation of the Tubes. Tube #1, (fig. 1), consisted of a glass tube 16 cm. long, 3 cm in diameter at the middle. The two electrodes were nickel disks 19 mm. in diameter and 2 mm. thick. The distance between the electrodes was 2 cm. Nickel was used for electrodes because it probably contains less gas, especially oxygen, at ordinary temperatures and pressures than platinum or silver and does not tarnish very readily.

In tube # 2, fig. 2, the bulb was 4 cm. in diameter. The upper electrode was a nickel disk 19 mm. in diameter and 2 mm. thick. The lower electrode was potassium for one set of experiments and caesium for another. The area of the potassium was about the same as that

of the nickel electrode; and of the caesium about 1 cm^2. The distance between the electrodes was 2 cm.

For the preparation of potassium a tube of the form shown in figure 3, plate II, page 8, was used. A piece of potassium was introduced into the tube through an opening at e and placed at a. The opening at e was then closed, and exhaustion by a Gaede pump begun. During the evacuation the tube f, containing the electrodes, was enclosed by a heating coil and kept at a temperature of 200°C. for about three hours, in order to remove as much as possible the gases occluded in the walls of the tube and in the electrodes, so that on subsequent heating gas would not be given off. The charcoal bulb d was heated to 300° or 400° during the exhaustion. When it was possible to pump the system down to a soft Röntgen ray vacuum with f and d still heated, then the heating coil was removed from f and the gas flame from under d and the exhaustion carried on to a hard Röntgen ray vacuum. The vacuum was tested by a discharge tube not shown in the diagram. The potassium was melted and the oily vapors from the crust pumped out during the melting. Potassium was then distilled over into the bulb b in the following manner: on carefully heating the potassium at a vapor went over into b and metallic potassium deposited on the walls of the bulb. The tube was then allowed to cool down and the process repeated. In this way sufficient potassium could be collected in b. The surface of the potassium obtained in this manner is as brilliant as polished silver. The whole system as shown in figure 3 was sealed off from the pump, the potassium poured into bulb c and the charcoal bulb placed in liquid air. After waiting 20 or 30 minutes for the charcoal to absorb the remaining gas the tube f was sealed off from the rest of the system at g. By this method of preparing a tube as good a vacuum as possible is obtained.

Plate II

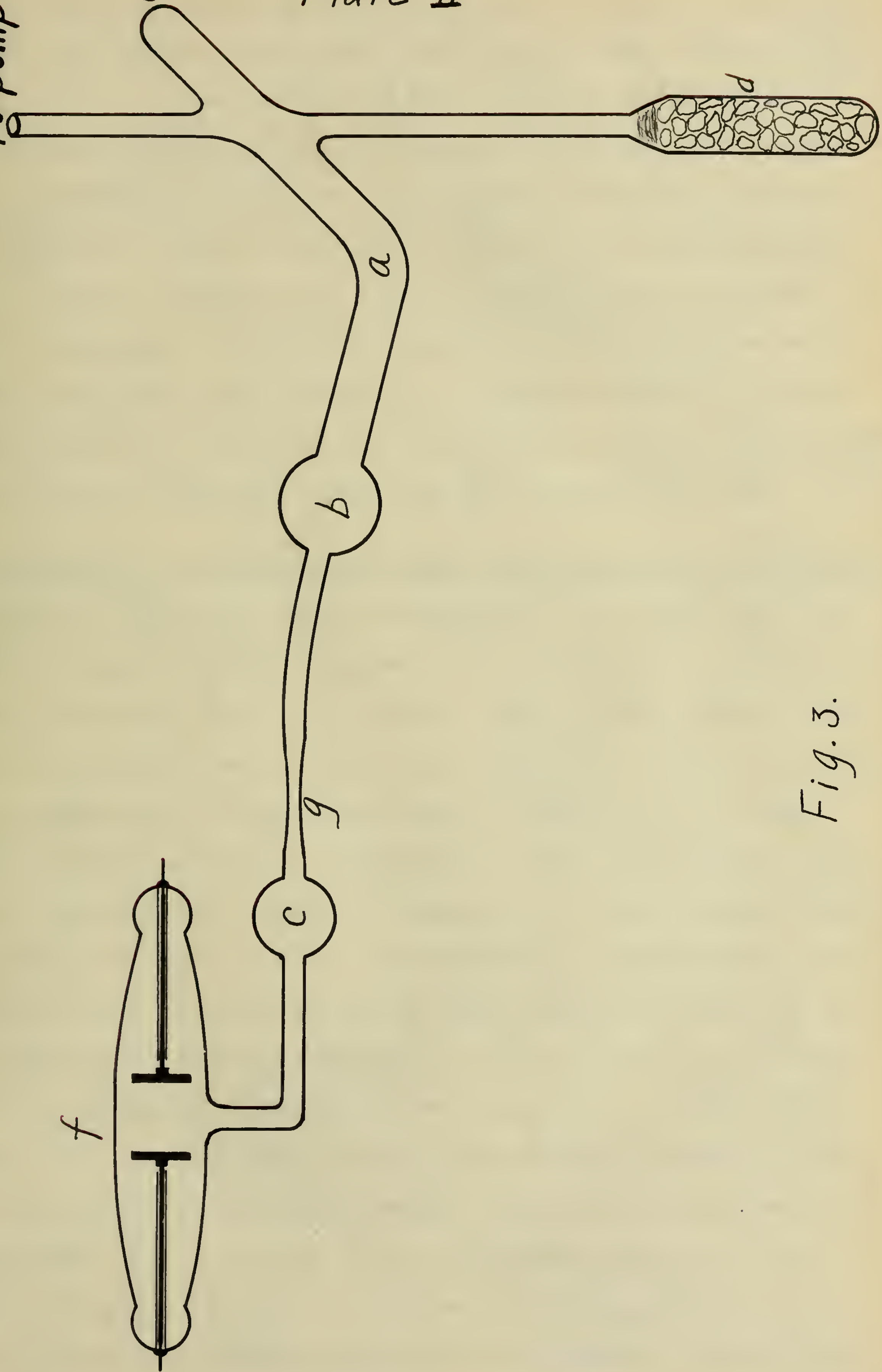


Fig. 3.

The method of preparing tube # 2, (fig. 2), was the same except that the potassium was poured into the tube and lodged at b (fig. 2) before it was sealed off from the rest of the system.

A similar method was used in preparing tube # 2 with caesium for one electrode, but with the following modification: the tube was closed with a rubber stopper at e (fig.3) and exhausted. Then the whole system including the pump was filled with nitrogen at atmospheric pressure. A small bulb in which the metallic caesium was contained was filled with nitrogen, the caesium melted and poured into the tube at e, which was then closed and exhaustion begun. From this point on the method of preparing the tube was the same.

Arrangement of Apparatus for Measuring Conductivity at Various Temperatures. The method used for measuring the conductivity of the alkali vapor is shown diagrammatically in figure 4, plate III, page 10. The tube (#1, fig. 1 or # 2, fig. 2) was placed in the heating coil H, which was enclosed in a sheet iron box C. This could be made light tight and the experiment was carried on in a dark room. The copper core of the coil and the sheet iron box were both grounded. A wire from electrode a passed thru a well polished hard rubber plug and was joined to a movable wire w which made connection with a water rheostat R. To the water rheostat were connected the terminals of a storage battery B_1 of 1800 volts and one terminal of the battery was grounded. From electrode b a wire passed through a well polished hard rubber plug and was connected to one pair of quadrants of the electrometer. The other pair of quadrants were grounded. k is a plunger key by which the electrode b and the pair of quadrants to which it is connected may be grounded. c is a collar of metal foil placed around the tube near the end and con-

Plate III.

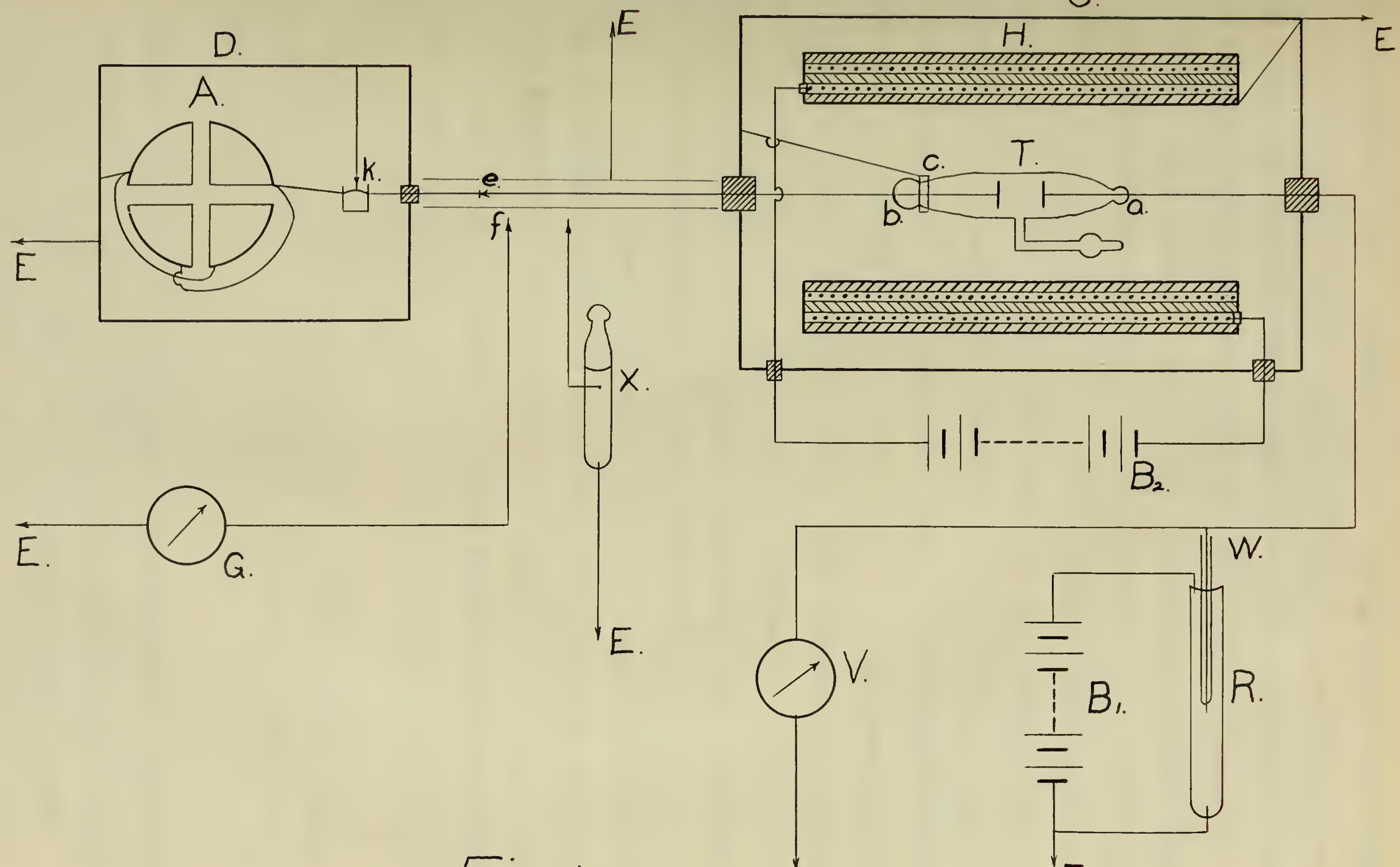


Fig. 4.

nected to earth so that conduction over the outside of the tube may be avoided. The electrometer and connecting wires were enclosed in a sheet iron box D which was grounded. The wire connecting electrode b to the electrometer was enclosed in a metal tube between C and D and this was also grounded. The scheme described above was used when the potential of electrode b was to be measured, and for measuring currents of the order of 10^{-13} to 10^{-11} amperes. When currents of the order 10^{-11} to 10^{-9} were to be measured one terminal of a high resistance X was connected to the wire running from b to A at e. The other terminal of X was grounded. When k was opened a current flowed from b through X to the earth and the electrometer deflection gave the fall of potential across this resistance. And from these two quantities the current can be computed. When currents greater than 10^{-9} were to be measured the wire from b was disconnected from the electrometer at e and connected to a wire f from a galvanometer. The other terminal of the galvanometer was grounded.

The potential applied at a was measured by one of three electrostatic voltmeters V of the Kelvin and White type. Three voltmeters were necessary to cover the range required by the investigation; the first read from 0 to 90 volts, the second from 100 to 600, the third from 500 to 1500.

When it was desired to pass a beam of light into the tube a slit in the box C was opened which was in line with the slit through the heating coil.

Heating Coil. The tube was kept at a temperature higher than room temperature by means of a heating coil or electric furnace. The core of the furnace consisted of a copper cylinder 10 cm. in diameter and 25 cm. long. At the middle of the cylinder two slits were

cut, opposite to each other, 1.5 cm. by 0.5 cm., through which a beam of light could be directed into the tube placed inside the coil The cylinder was covered with asbestos and a layer of # 16 german silver wire wound on, 8 turns to the inch. This was covered with asbestos and a second layer wound on with the same number of turns, and this was covered with a heavy layer of asbestos. The two layers of wire were so connected that the magnetic field arising from the current through one would be opposed by the magnetic field of the other. With this arrangement the magnetic force within the cylinder was found to be so slight as not to effect appreciable the movement of ions in the tube.

Galvanometer. The galvanometer used was a D'Arsonval instrument, manufactured by W.G. Pye, Cambridge. The resistance was 122 ohms, and its period 9 seconds. The deflections were read by a telescope and scale at a distance of 2.5 meters. One millimeter deflection indicated a current of 0.837×10^{-9} amperes.

High Resistance. The high resistance used was a liquid resistance, consisting of meta-xylol with a few drops of absolute alcohol. The resistance could easily be changed by varying the proportion of meta-xylol and alcohol. The container consisted of a glass tube 0.9 cm. in diameter and 8.0 cm. long, with two platinum electrodes sealed through the glass 3.5 cm. apart. The tube was closed by a ground glass stopper. The resistance was observed to increase with time, probably due to evaporation of alcohol. But the resistance was constant for a period of a few hours required for a set of readings. The resistance used varied from 4.72×10^{9} ohms to 14.3×10^{10} ohms.

Experimental Results.

Tube # 1. Potassium in Bulb c. The first series of measurements which will be presented were taken with tube # 1, (fig. 1), with potassium in bulb c and with the tube in the dark. The method of taking the readings was as follows: the potentail was applied at electrode a with the key k closed, so that the charge which would arise from electrostatic induction which would occur in the electrode b and connecting wire would be removed by the connection to earth through k. Potentials as high as 1690 volts were applied. At 25°, 50 and 75°C. nothing of the character of a regular conductivity was observed. But a phenomenon which has not been reported before was observed. On opening the key k , after a positive potential was applied at a the electrometer gave a positive deflection which very soon came to a maximum. Then there was a movement of the electrometer needle toward the negative which was nearly of a constant rate. A test was made to determine whether this was a charge or a constant current. With a + 100 volts applied at a this movement of the electrometer toward the negative continued for three hours and fifty minutes, and the rate of deflection was nearly constant for the first 50 minutes. After the maximum negative deflection had been reached the electrometer needle drifted toward the zero at the rate of 0.5 mm. per minute which was about the rate of the natural leak. So we would conclude that the effect is of the nature of a charge which at the temperature of 25° builds up very slowly and at first the rate of increase is a linear function of the time.

When a negative potential was applied the results were similar except that the directions of deflections were reversed. It was also observed that if a higher potential was applied after observations had been made for a given potential the"negative" current was not as

large as was the case when a period of rest was given the tube with both electrodes grounded. Consequently it was found necessary in taking a set of readings to leave the tube earthed by both electrodes for 10 minutes between the measurement of the current for a given potential and the measurement for the next higher potential. Furthermore it was noticed that if the tube was exposed to light while a potential was applied at a, there was a larger positive deflection and after the light was turned off the "negative" current was larger than before. After sufficient time in the dark the "negative" decreased to a constant value.

In table I there are given data which show the relation between the potential applied and the "positive" charge, that is, the first electrometer deflection after opening the key, which is in the same direction as the field; and also the relation between the potential applied and the"negative" effect, which is a current appearing after the "positive " charge reaches a maximum and is in a direction opposite to the field. The "negative" current was measured by the rate of deflection of the electrometer. The curves of plates IV, V and VI, (pages 16, 17, and 18), are plotted from the data of table I, p. 15. The curves of plate IV show that the"positive"charge is a linear function of the potential and is smaller for 50° than for 25°. The curves of plates V and VI show how the "negative " current increases with the potential. The remarkable feature of this phenomenon is that even with a potential of 1700 volts there is a current in the opposite direction to what we would expect from our present knowledge of conductivity in solids and in gases. The "negative" current is greater for 50° than for 25° (the ordinates of plate VI have a larger value than those of plate V) and this accounts for the fact that the "positive" charge is less for 50° than for 25°, as the

deflection obtained at any one instant must be the resultant of these two effects.

Table I

"Positive" Charge and "Negative" Current at 25°

Potential in Volts	"Positive" Charge	"Negative" Current
+ 100	+ 4.3	- 0.4
200	7.3	0.85
300	12.0	1.2
500	19.8	2.0
700	25.7	2.8
900	35.5	3.5
1078	44.4	4.5
1488	off scale	5.5
1690	" "	6.2
- 100	- 3.8	+ 0.47
200	3.1	0.85
300	12.6	1.2
500	22.8	1.9
700	29.9	2.55
900	39.0	3.0
1078	49.9	3.6
1283	off scale	4.3
1488	" "	5.0
1690	" "	5.2

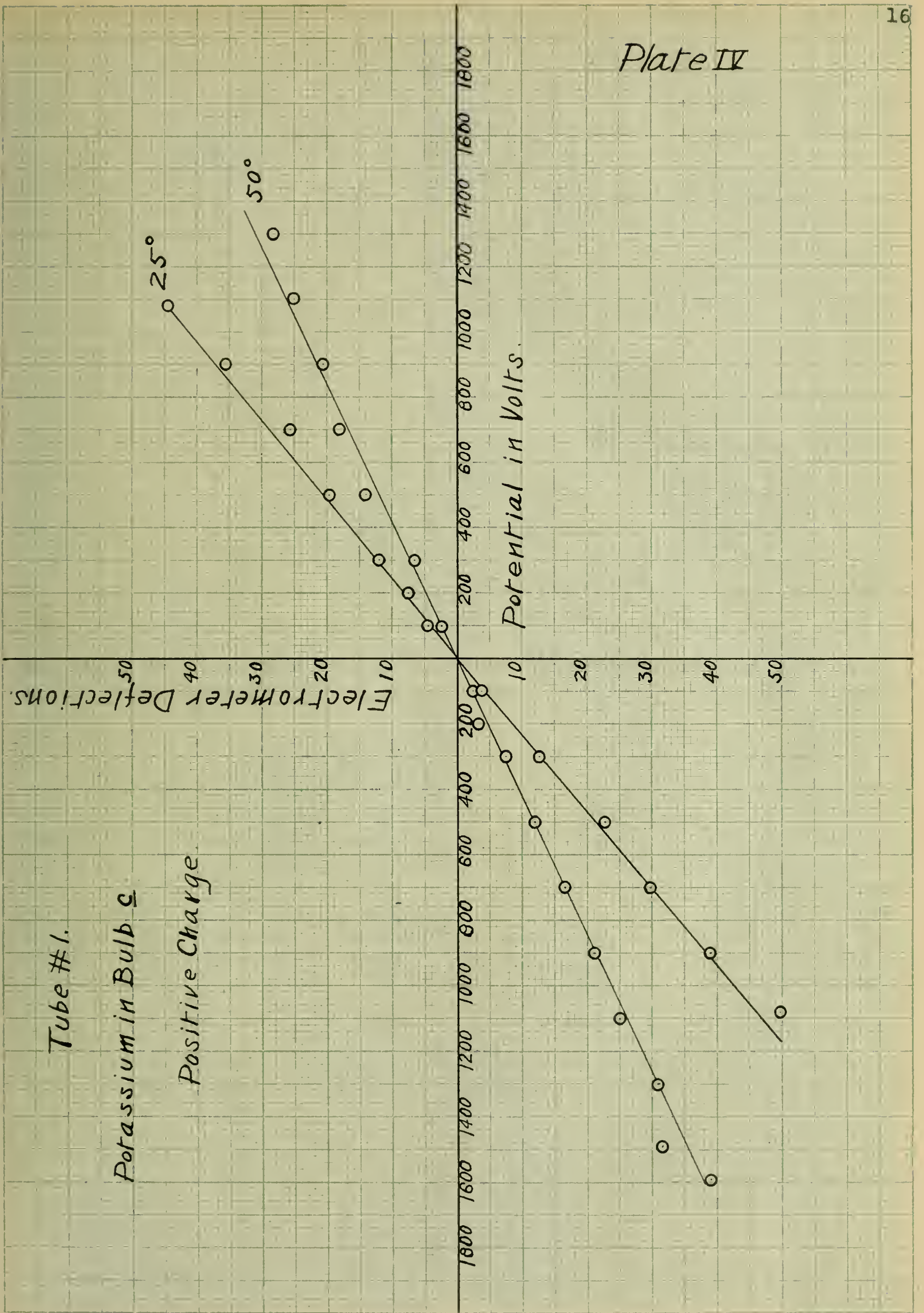
"Positive" Charge and "Negative" Current at 50°

Potential in Volts	"Positive" Charge	"Negative" Current
+ 100	+ 2.5	- 6.2
300	6.5	16.2
500	14.0	24.8
700	18.0	36.0
900	20.5	47.0
1100	25.0	58.0
1300	28.0	72.0
1490	off scale	110.7
1690	" "	111.0
- 100	- 2.5	+ 5.6
300	7.5	16.0
500	12.0	26.6
700	16.5	37.0
900	21.0	47.4
1100	25.0	58.0
1300	31.0	66.0
1490	31.5	84.0
1690	39.0	97.0

When the tube was heated up to 75° the "positive" charge did not appear, but immediately on opening the key there was a "Negative" deflection. The initial "negative" current was much larger than at lower temperatures, but the effect shows more the character of a charge in that it came to a maximum much sooner.

The variation of the initial "negative" current and charge with the temperature is shown by table II, p. 19, and the curves of plates VII and VIII, pages 20 and 21. In taking these readings a constant potential of +400 volts was maintained. It was impossible to measure the currents by this method temperatures higher than 75°. The "charge" curve shows that the effect reaches a maximum between 65° and 70°. And if the curve is extended until it cuts the axis of

Plate IV



Tube #1.
Potassium in Bulb c
Positive Charge
Electrometer Deflections.
Potential in Volts.
25°
50°
10
20
30
40
50
200
400
600
800
1000
1200
1400
1600
1800

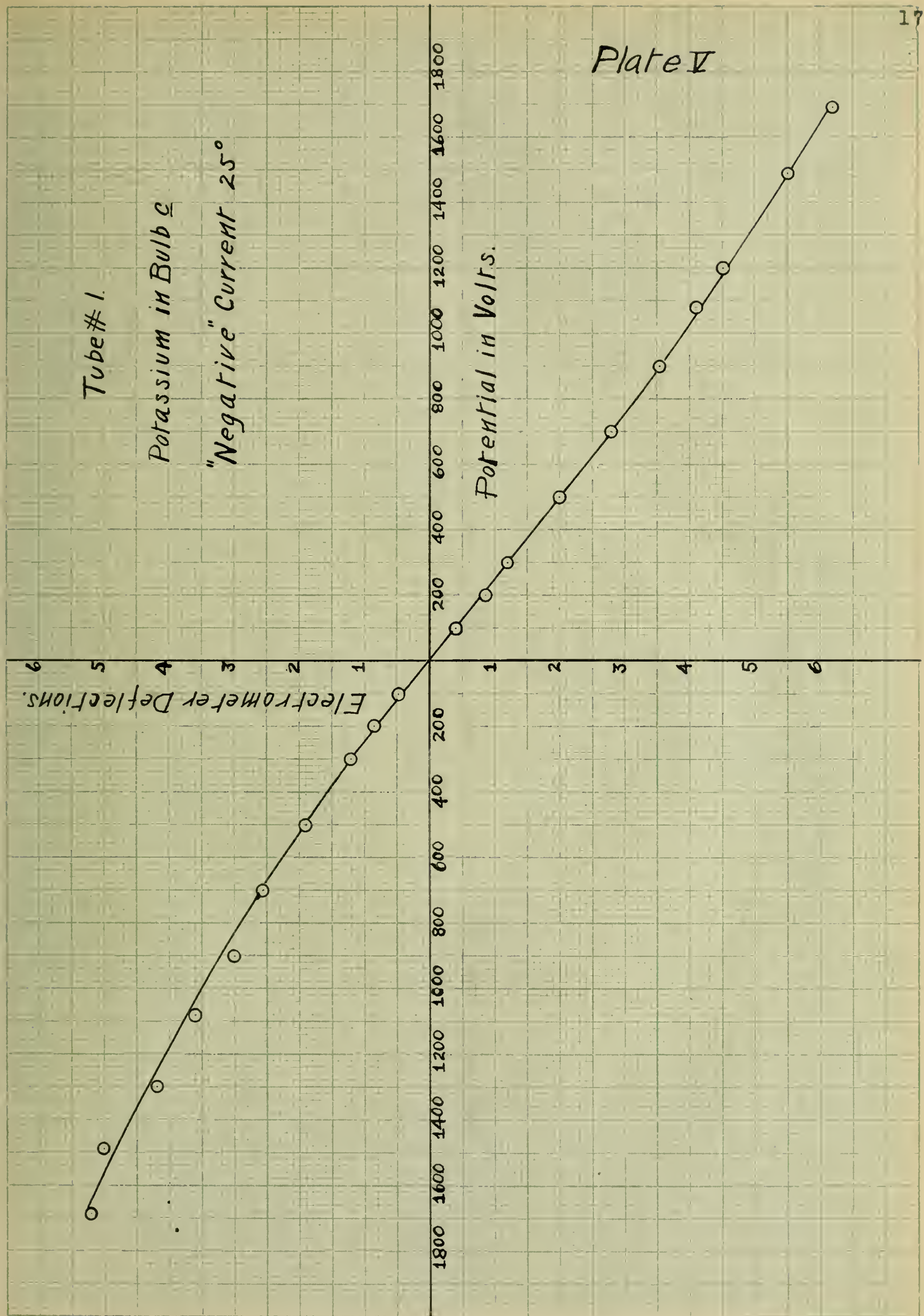
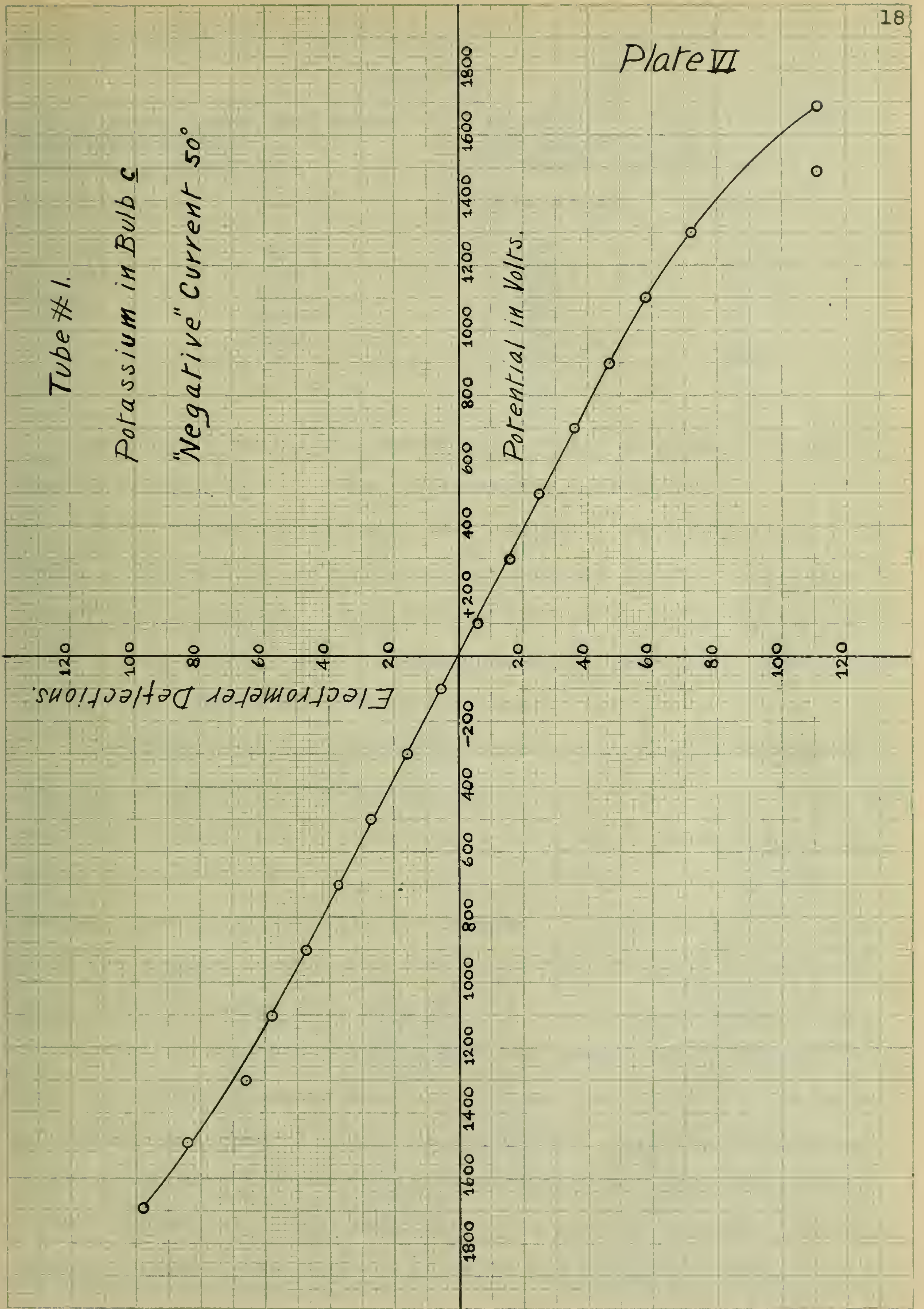


Plate V
Tube # 1.
Potassium in Bulb c
"Negative" Current 25°
Potential in Volts.
Electrometer Deflections.
200 400 600 800 1000 1200 1400 1600 1800
1 2 3 4 5 6

Plate VI


Tube # 1.
Potassium in Bulb c
"Negative" Current 50°
Potential in Volts.
Electrometer Deflections.

abscissae, it would appear that the effect disappears at about 104°.

Table II

Variation of "Negative" Current with Temperature.
Potential + 400 Volts.

Temperature	Current
25°	- 1.45
38.5	8.2
50	22.0
60	55.7
70	72.5

Variation of "Negative" Charge with Temperature.
Potential + 400 Volts.

Temperature	Charge
25°	- 9.2
38.5	13.75
50	21.9
60	26.0
70	27.7
80	22.0
90	14.0
100	4.0

In tables I and II the charge and current is given in terms of the scale divisions of the electrometer deflections.

At 100° when the potential was gradually increased up to + 700 volts a reversal of the electrometer suddenly occured, and there was a very large positive deflection accompanied by a lighting up of the tube, There is,then, at this temperature and pressure a conductivity of the usual character through the vapor.

In order to determine whether or not this "negative" effect was due to anything else besides the potassium vapor, a new tube was made of the same form and dimensions in which no potassium was present. The new tube was made with new electrodes, from new glass tubing thoroughly cleaned. The cocoanut charcoal used for exhaustion was freshly burned. The tube was pumped out with a new Gaede pump which had never been used for the exhaustion of tubes where alkali metals were present. The tube was pumped out to a hard Röntgen ray vacuum, the charcoal bulb immersed in liquid air for about 20 minutes and then the tube was sealed off. This tube showed the same "negative"effect as the one with potassium vapor. When first tried, immediately after sealing off, it gave no positive deflection when a positive potential was applied, but a negative deflection

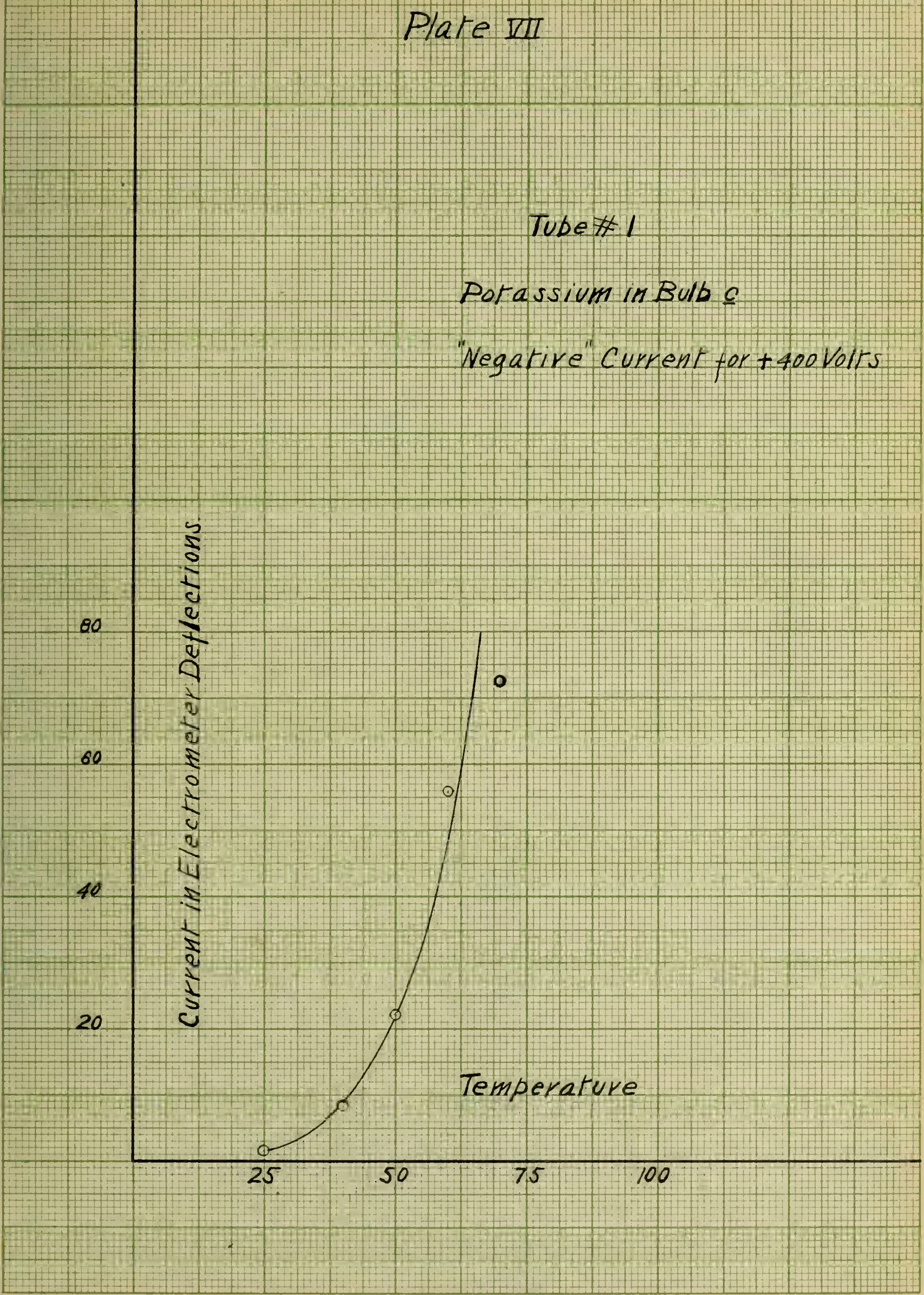
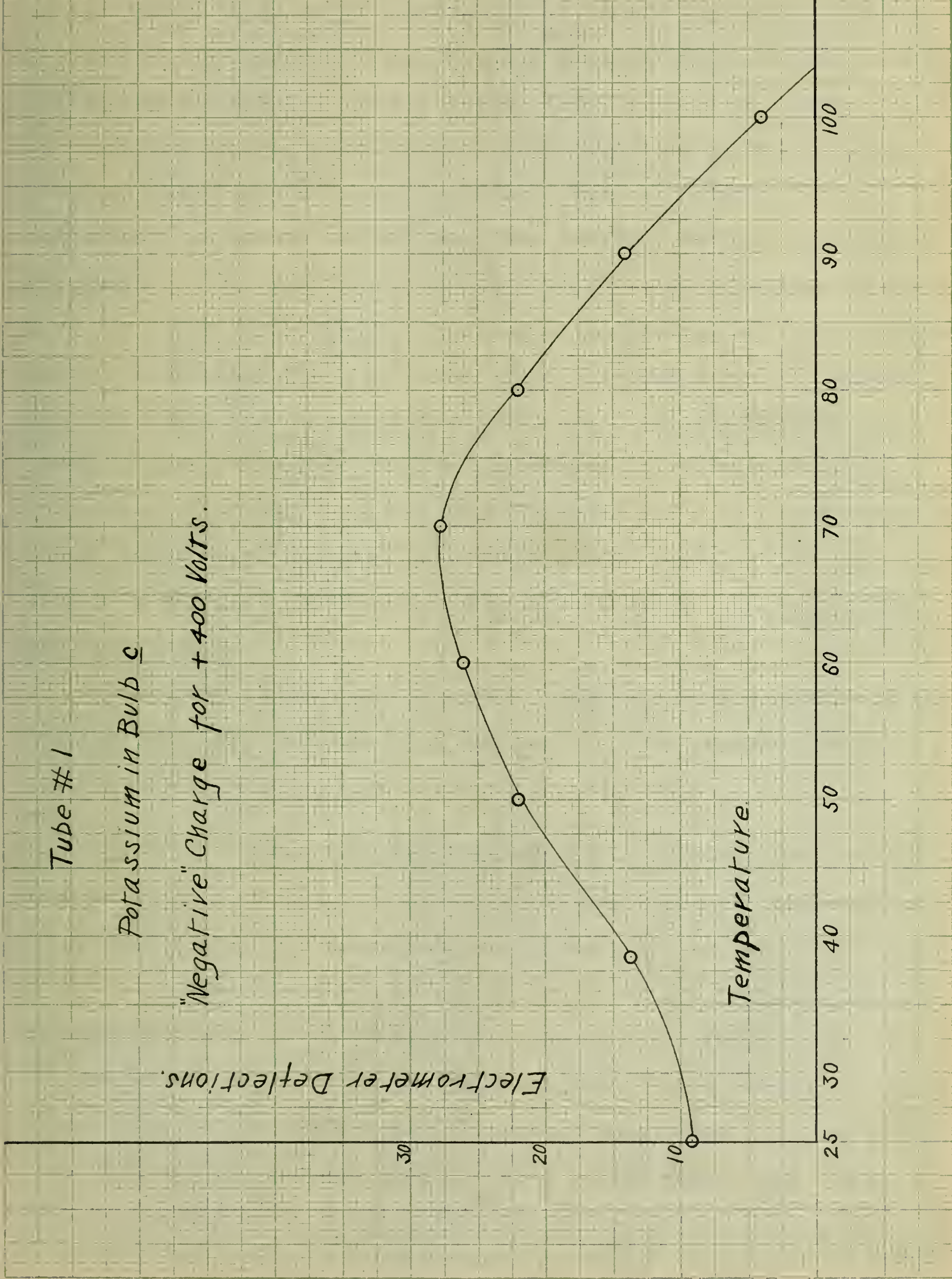


Plate VII
Tube # 1
Potassium in Bulb c
"Negative" Current for +400 Volts
Current in Electrometer Deflections
80
60
40
20
Temperature
25
50
75
100

Plate VIII


Tube #1
Potassium in Bulb c
"Negative" Charge for +400 Volts.
Electrometer Deflections.
Temperature
10
20
30
25
30
40
50
60
70
80
90
100

the rate of which was about five times as great as that observed in the former case. After leaving in the dark and grounded by both electrodes for 10 hours there was then observed, when a positive potential was applied and the key opened, first a positive charge, which was followed by a negative current which was smaller than the one observed when the tube was first tried. When a 16 candle power incandescent lamp shone on the tube, the negative current increased and the positive charge entirely disappeared. After leaving in the dark for a few hours the positive charge reappeared and the negative current decreased. Hence it seems that this phenomenon (1) arises from the glass tube or the metal electrodes, (2) is effected by light, (3) and is diminished by the presence of potassium vapor. Four tubes with similar electrodes of nickel and containing potassium vapor, one tube with nickel electrodes and no alkali vapor, and one tube with aluminum electrodes and no alkali vapor, all showed the same phenomenon.

No attempt is made at this time to explain this effect, but the observations made are presented and must be taken account of in measurements of small conductivities through gases.

Tube # 1. Potassium between Electrodes. As the vapor of potassium shows no spontaneous ionization for the range of temperatures and potentials used, the next problem that presents itself is whether or not the potassium gives off particles which are carriers of electricity. For this investigation the potassium in bulb c (fig, 1) was melted and poured into the main tube and lodged between the electrodes, but not in contact with either of them. For this work a new tube was made of the same form and size as the first used, in as much as heating up to 100° a little potassium had distilled over in-

to the end bulbs and on to the electrodes. This new tube was tested out first with the potassium only in bulb c. It was found to show the same effect of a positive charge followed by a negative current when a positive potential was applied. The "negative"current for + 300 volts and - 500 volts was measured and found to be almost identically the same as for tube # 1. The potassium was then melted and poured into the main tube and placed as nearly as possible mid-way between the two electrodes. Observations were made of the currents for temperatures 25°, 50°, 100°, and 150° with the tube in darkness and with the potassium illuminated by a beam of light. The source of this light was a 16 candle power, incandescent, carbon filament lamp, supplied from a storage battery of 120 volts. The beam of light did not fall on the nickel electrodes, though of course some reflected light did reach them. The results obtained are given in table III, page 24 and are shown graphically by the curves of plates IX, X, and XI, pages 26, 27 and 28. The curves in black give the currents when the tube was in darkness. Those in red give the current when the potassium was illuminated. The dotted portions of some of the curves indicate that these parts were only determined qualitatively. Quantitative measurements were impossible.

Attention is called to four points shown in these curves: (1) the "negative" effect persists for 25° and 50° in darkness and is of the same order of magnitude as occured in the former case; this disappears for 100° in darkness and for 25° and 50° when the potassium was illuminated: (2) the linear character of the curve for 100° "in darkness" and the abrupt bend in the negative branch at 875 volts; (3) for 25°, 50° and 100° "potassium illuminated" the positives branches of the curves show larger currents than the negative; (4) for 100° and 150° there is a negative current when no potential is

applied. The peculiarities can be better explained later after the presentation of the phenomena of tube # 2.

Table III

Tube # 1, Potassium between Electrodes. Temperature 25°

In Darkness		Potassium Illuminated	
Potential in Volts.	Current in Amp.	Potential in Volts.	Current in Amperes.
+ 300	-0.092×10^{-12}	+ 0	$+0.01\times10^{-12}$
700	0.232	+ 200	0.041
1070	0.328	400	0.111
1500	0.503	600	o.203
		800	0.304
		1000	o.405
		1200	0.508
		1400	0.64
		1600	0.678
- 300	$+0.092\times10^{-12}$	- 200	-0.02×10^{-12}
700	0.223	400	0.02
1100	0.348	600	0.054
1500	0.510	800	0.071
		1000	0.095
		1200	0.111
		1400	0.122
		1600	0.132

Temperature 50°

+ 300	-0.56×10^{-12}	0	+0.061
700	1.165	+ 200	0.81
1100	2.13	400	1.74
1500	3.00	600	2.50
		800	3.18
		1000	3.73
		1200	4.20
		1400	4.72
		1600	5.20
- 300	$+0.58\times10^{-12}$	- 200	-0.405×10^{-12}
700	1.23	400	o.72
1100	1.985	600	0.912
1500	2.71	800	1.055
		1000	1.195
		1200	1.33
		1400	1.48
		1600	1.62

Table III (Con'd)

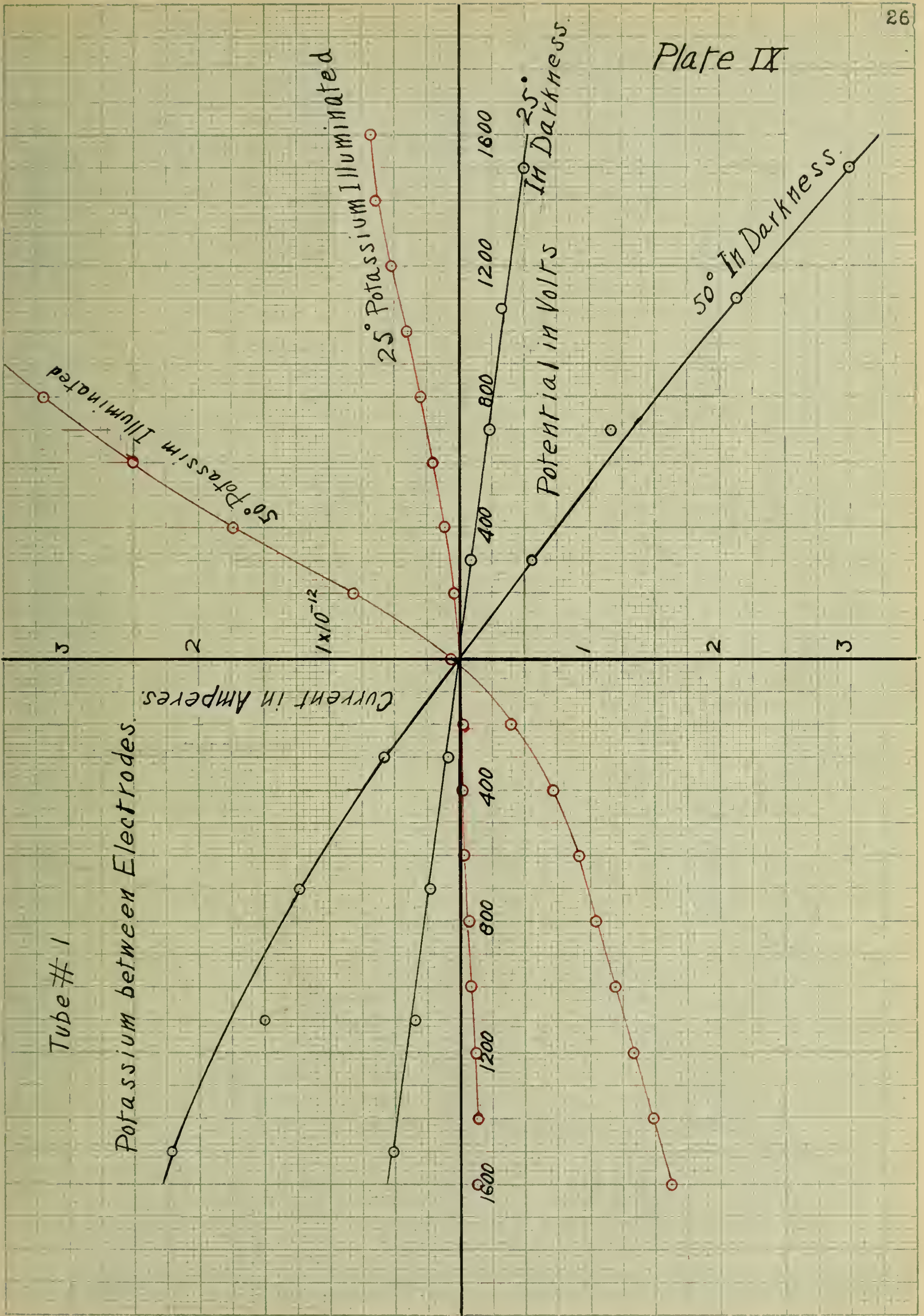
Temperature 100°

In Darkness		Potassium Illuminated	
Potential in Volts.	Current in Amperes.	Potential in Volts.	Current in Amperes.
0	-0.243×10^{-12}	0	-0.79×10^{-12}
+ 200	+0.528	+ 50	+ 1.77
400	1.26	100	5.52
600	1.9	150	6.55
800	2.62	200	8.53
1000	3.44	250	10.24
1200	4.0		
1400	4.61		
1600	5.175		
- 200	-1.095	- 50	- 3.63
400	1.93	100	4.57
600	2.74	150	4.98
800	3.76	200	6.14
875	4.16	250	6.8
905	off scale	300	7.6
		350	8.82
		820	off scale

Temperature 150°

In Darkness		Potassium Illuminated	
Potential in Volts.	Current in Amperes.	Potential in Volts.	Current in Amperes.
0	-5.6×10^{-12}	0	-6.5×10^{-12}
+ 50	- 1.12	+ 50	+ 0.7
100	+ 2.59	100	6.22
200	9.37	200	17.35
300	14.63	300	28.0
400	18.4	400	37.9
500	21.88	490	50.3
600	25.3	495	167.5
660	29.6		
667	34.7		
670	off scale		
- 50	- 6.77	0	- 7.0
100	9.97	- 50	11.63
200	16.8	100	16.8
300	25.2	200	30.8
400	34.3	270	46.2
450	44.8	300	off scale
452	off scale		

Plate IX


Tube # 1
Potassium between Electrodes.
Potential in Volts
Current in Amperes.
1x10^-12
25° Potassium Illuminated
50° Potassium Illuminated
25° In Darkness.
50° In Darkness.
400
800
1200
1600
1
2
3

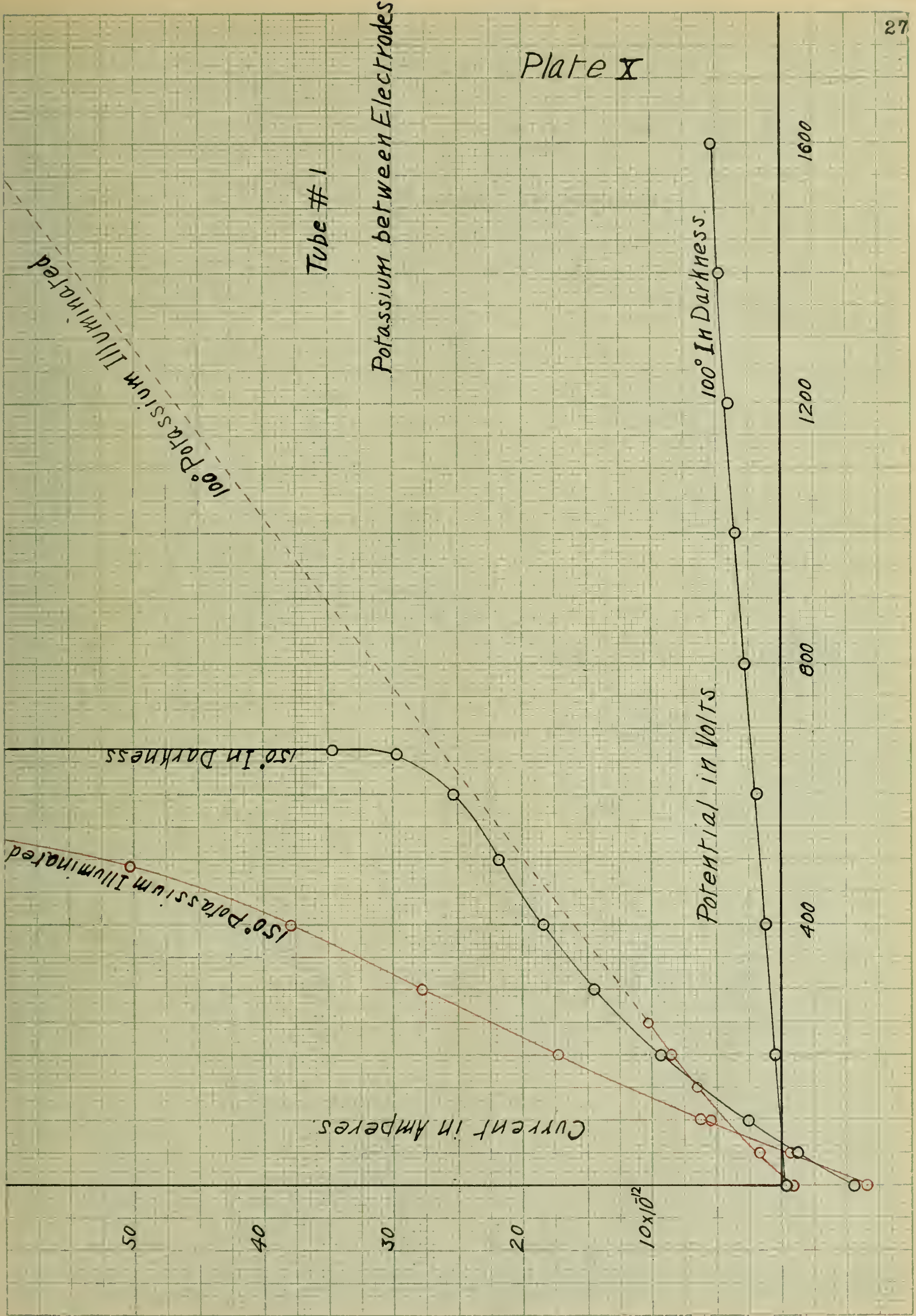
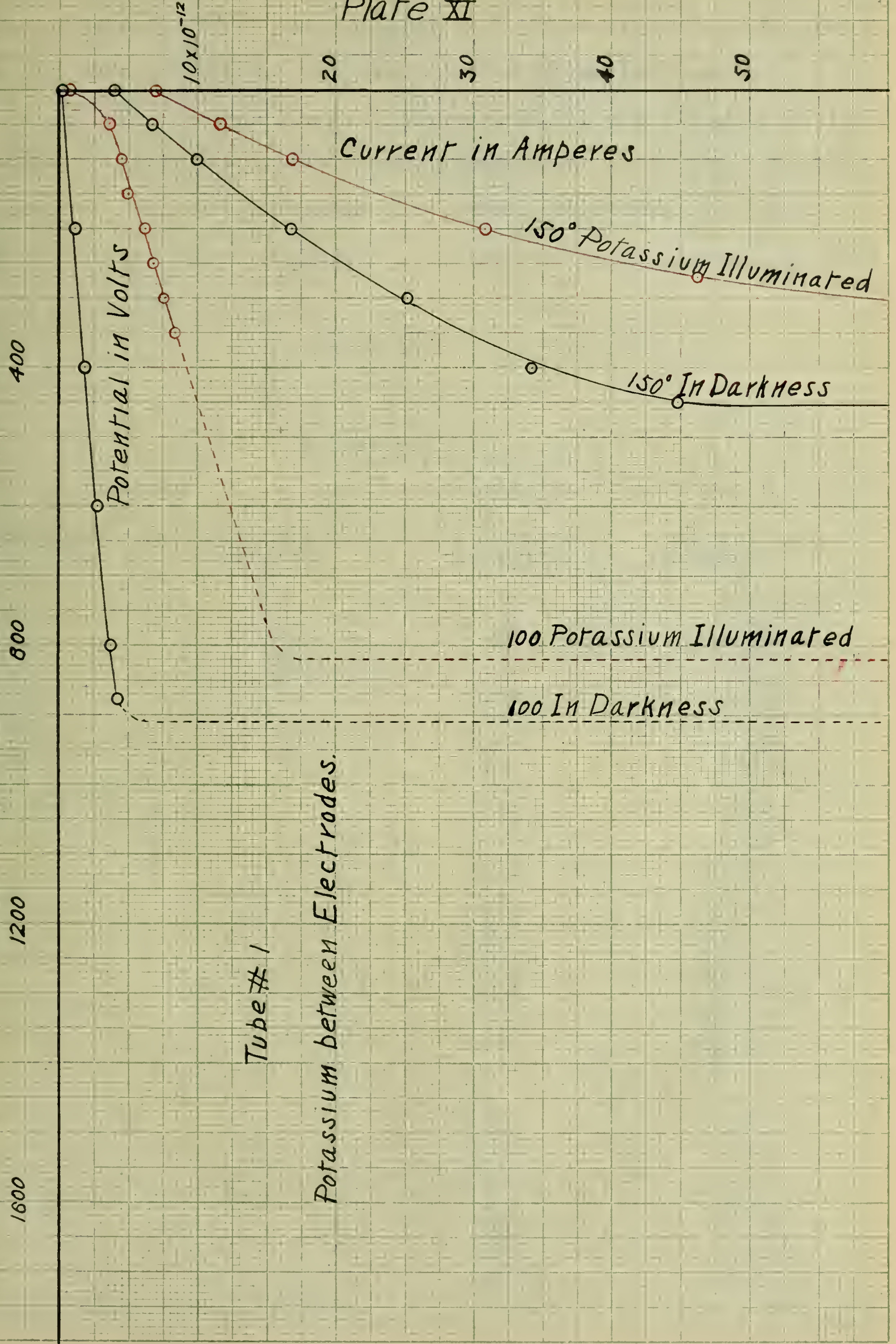


Plate X
Tube #1
Potassium between Electrodes
100° In Darkness.
100° Potassium Illuminated
150° In Darkness
150° Potassium Illuminated
Potential in Volts
Current in Amperes.
1600
1200
800
400
50
40
30
20
10x10^{-12}

Plate XI


10x10^-12
20
30
40
50
Current in Amperes
150° Potassium Illuminated
150° In Darkness
100 Potassium Illuminated
100 In Darkness
400
800
1200
1600
Potential in Volts
Tube # 1
Potassium between Electrodes.

Tube # 2. Potassium. This tube gives more nearly than tube # 1 the conditions that are realized in a photo-electric cell prepared for determining the maximum positive potentials assumed by a metal under the action of light. The conductivity was measured with the tube "in darkness" and with the "potassium illuminated" at the temperatures 25°. 50°, 100° and 150°. The results are given in table IV and are shown graphically by the curves of plates XII, XIII XIV, XV XVI, and XVII.

Table IV.

Tube # 2. Potassium.

Temperature 25°

In Darkness		Potassium Illuminated	
Potential in Volts	Current in Amperes	Potential in Volts	Current in Amperes.
		0	+ 0.075×10^{-10}
		+ 25	1.55
		50	2.05
		75	2.5
		100	3.12
		150	4.0
		200	4.825
		250	5.625
		300	6.5
		350	7.54
		400	8.75
		450	10.45
		500	12.05
		550	15.25
		600	20.1
		650	29.2
		700	37.6
		750	51.8
		800	65.2
		850	108.5
		900	175.5
		- 25	-0.12
		50	o.09
		100	0.003
		200	0.000
		400	0.000
		600	0,000
		700	0.003
		800	0.006

Table IV (Con'd)

Temperature 50°

In Darkness		Potassium Illuminated	
Potential in Volts	Current in Amperes	Potential in Volts	Current in Amperes
0	-0.056×10^{-10}	0	-0.242×10^{-10}
+100	0.057	+ 25	+ 1.09
300	0.038	50	1.745
500	0.042	100	2.43
550	0.042	150	3.74
565	+ 3.3	200	5.26
570	4.25	250	7.16
580	8.25	300	10.3
		350	16.0
		375	20.9
		400	31.0
		415	37.7
		420	50.25
		421	off scale
-100	- 0.047	- 25	- 0.14
300	0.033	50	0.087
350	0.039	100	0.052
380	0.04	150	0.07
385	0.705	200	0.07
390	7.45	250	0.105
395	41.8	300	0.209
400	86.3	325	2.09
410	250.0	335	18.0
		350	113.0
		390	1170.0

Temperature 100°

In Darkness		Potassium Illuminated	
Potential in Volts	Current in Amperes	Potential in Volts	Current in Amperes
0	-4.45×10^{-10}	0	-4.3×10^{-10}
+100	2.29	+ 100	2.27
200	0.156	200	9.77
300	+ 1.156	300	23.8
400	3.12	350	34.4
450	3.91	390	52.4
457	22.2	450	121.0
460	off scale	465	off scale
0	- 4.37	0	- 4.3
-100	8.6	- 100	11.5
200	14.3	200	16.4
300	22.2	250	19.1
348	41.9	300	21.8
360	555.0	344	46.8
		348	104.5
		351	171.0
		355	360.0
		360	905.0

[illegible]

Table IV (Con'd)

Temperature 150°

In Darkness		Potassium Illuminated	
Potential in Volts	Current in Amperes	Potential in Volts	Current in Amperes
0	$-\ 2.4 \times 10^{-9}$	0	$-\ 2.1 \times 10^{-9}$
+ 20	+ 0.67	+ 28	+ 0.42
64	3.18	56	3.35
100	6.7	100	7.1
168	14.2	150	11.7
225	20.4	200	14.05
300	27.6	250	21.0
350	32.6	300	25.1
380	35.2	350	34.2
392	36.8	360	38.5
395	off scale	370	45.05
		380	54.4
		390	69.5
		400	101.0
		410	196.0
- 52	- 6.7	- 51	- 5.7
100	9.03	100	9.7
125	10.7	150	14.65
150	11.7	200	18.7
175	13.4	250	23.1
200	15.05	300	27.6
225	16.15	325	31.4
250	17.2	340	33.1
275	18.4	343	209.0
300	19.65		
325	20.9		
343	25.9		
350	73.6		
355	212.0		

One of the most interesting points brought out by this series of readings is the existence of a negative current when no electric field is applied. The data of the table show this to a better extent than the curves. This phenomenon was observed and has been investigated by J.W. Woodrow in this laboratory. This effect is apparent at 25° in darkness and at 50°, 100° and 150° with the potassium illuminated as well as in darkness. Woodrow has found this effect characteristic of the alkali metals. In table V , page 32 there are given data for the potential curves, plate XVIII, and the cur-

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

rent curves, plate XIX, for potassium and caesium. The potential curves show the increase with time of the potential of the alkali metal electrode when connected to the electrometer, electrode a being grounded. The current curves show the icrease of the current with the temperature. These curves are introduced here because of their bearing upon the author's results and as a confirmation of Woodrow's observations.

Table V

Emission of Positive Particles from Alkali Metals.

Potential Curves.

Potassium	
Time in Minutes	Potential in Volts
2	0.3
5	0.69
7	0.87
10	1.1
15	1.38
25	1.77
35	2.0
45	2.15
65	2.21
80	2.38
90	2.41
Caesium	
1	1.02
3	1.54
4	1.67
5	1.74
12	1.9
15	1.91
20	1.92
25	1.92

Current Curves

Potassium	
Temperature	Current in Amperes
25°	$- 0.028\times10^{-11}$
50°	0.56
100°	44.1
150°	240.0
200	21000.0
Caesium	
25°	$- 1.83\times10^{-12}$
40°	5.94
70°	14.0
100°	52.0

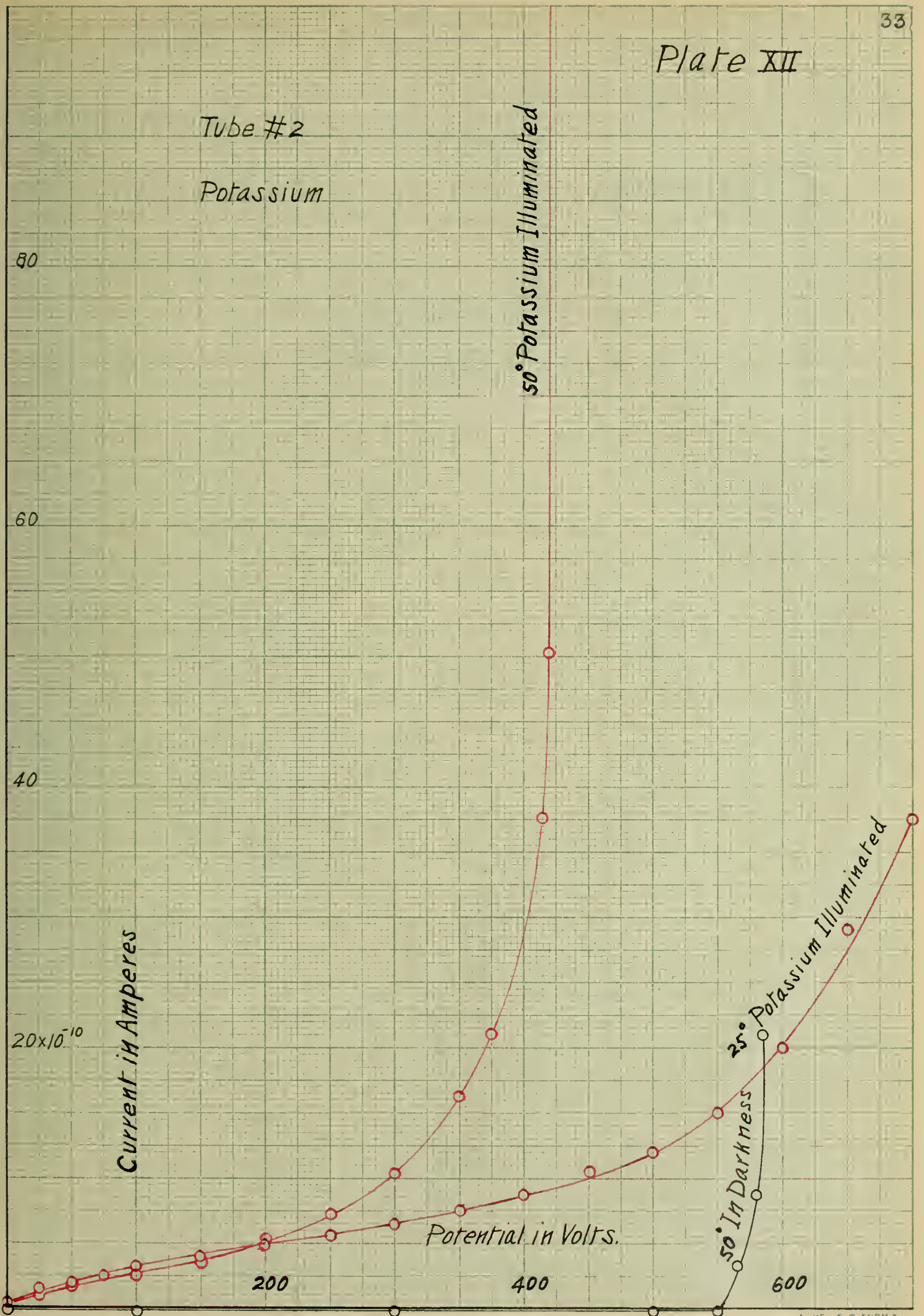
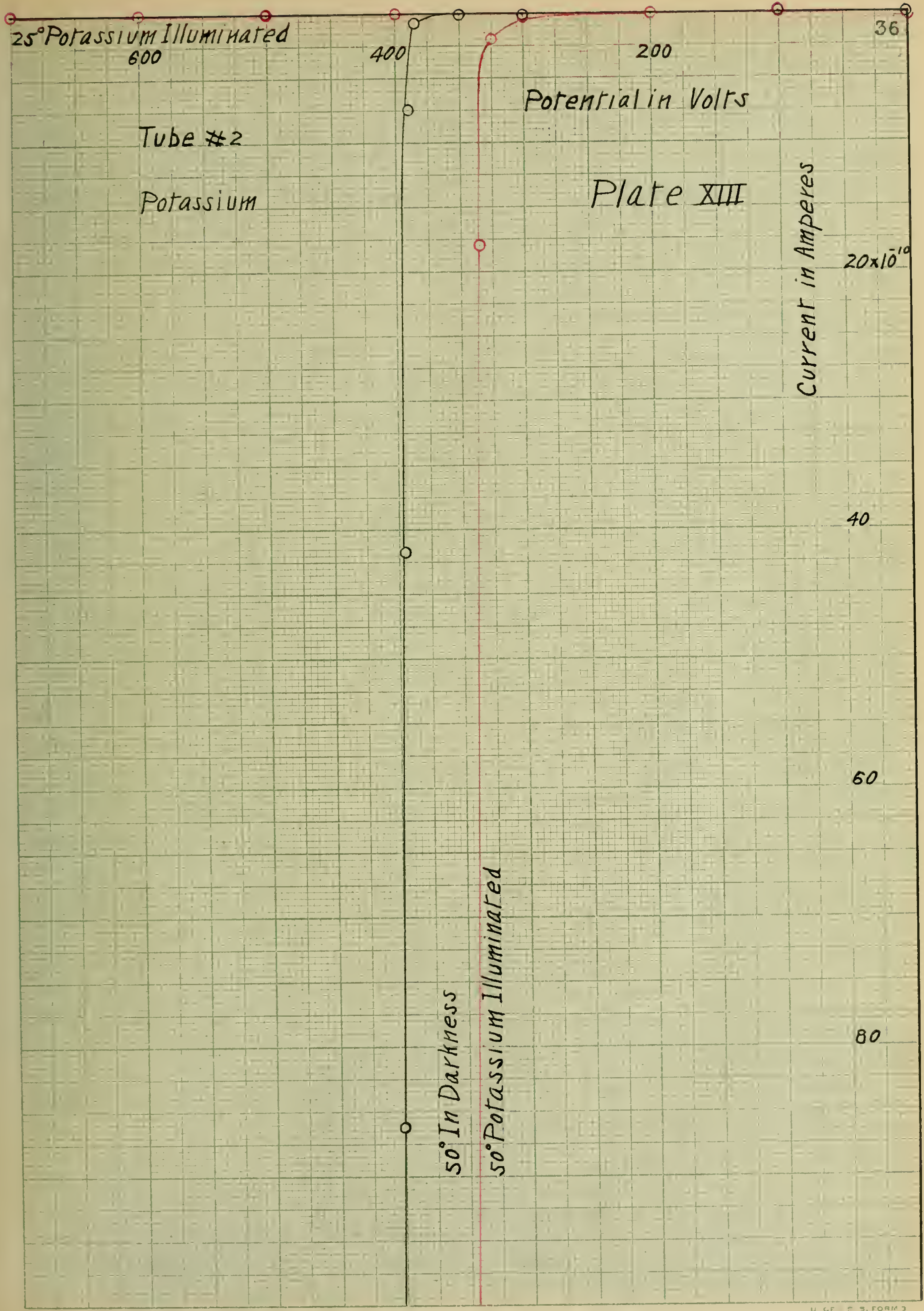


Plate XII
Tube #2
Potassium
50° Potassium Illuminated
25° Potassium Illuminated
50° In Darkness
Current in Amperes
Potential in Volts.
80
60
40
20x10^{-10}
200
400
600


25° Potassium Illuminated
600
400
200
Potential in Volts
Tube #2
Potassium
Plate XIII
Current in Amperes
20×10^{-10}
40
60
80
50° In Darkness
50° Potassium Illuminated

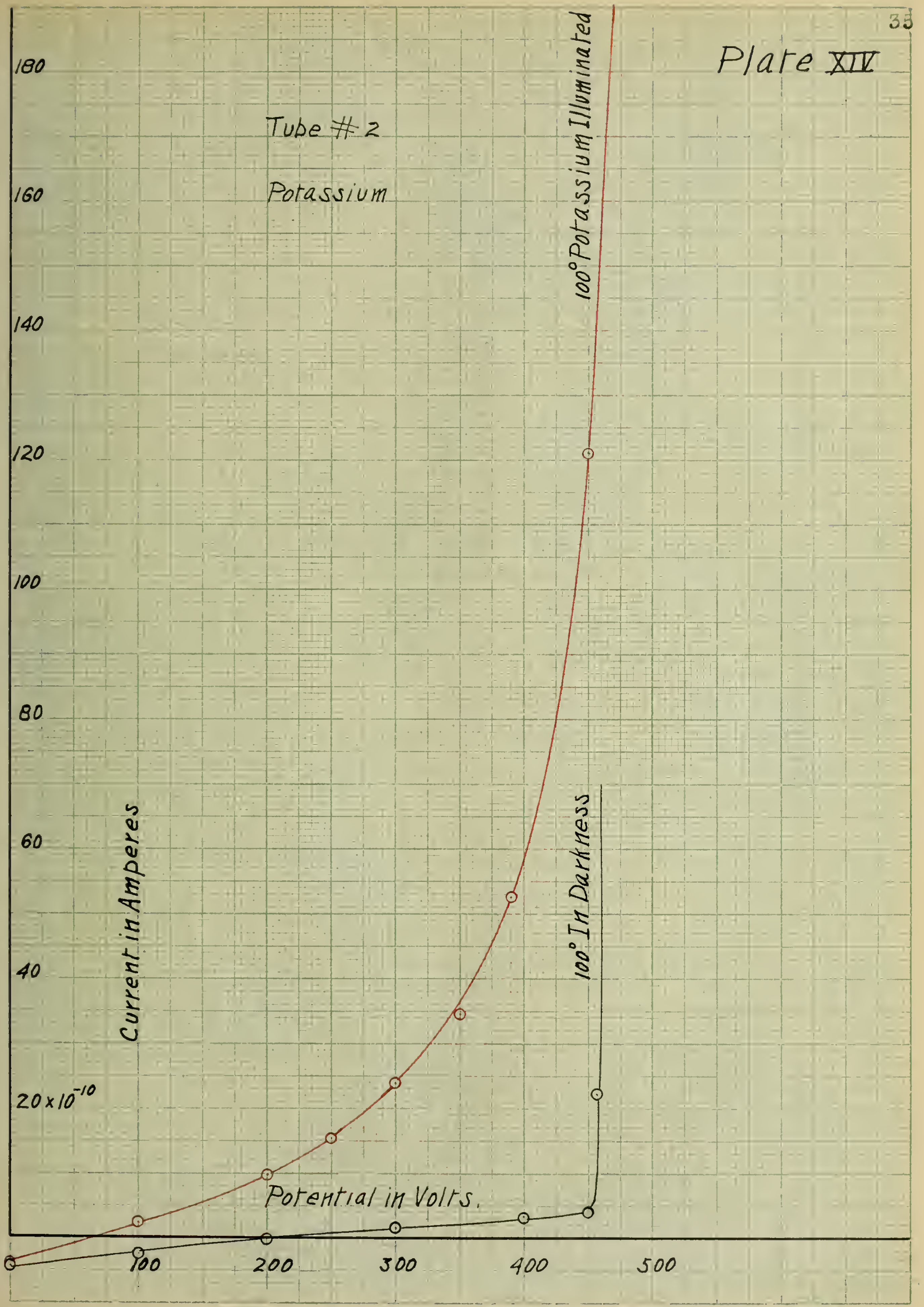
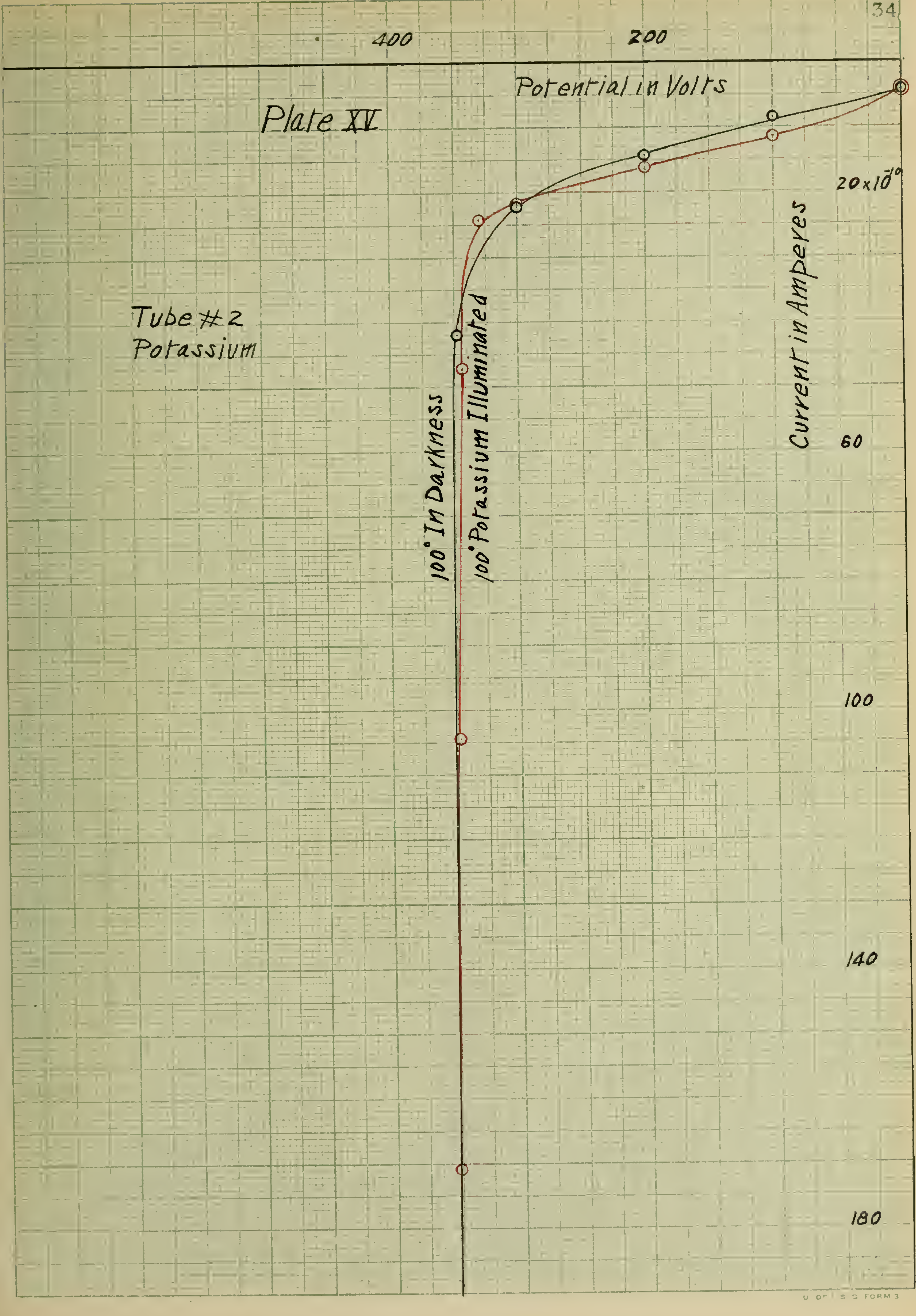


Plate XIV
Tube # 2
Potassium
100° Potassium Illuminated
100° In Darkness
Current in Amperes
Potential in Volts.
180
160
140
120
100
80
60
40
20 x 10^-10
100
200
300
400
500


400
200
Potential in Volts
Plate XV
20x10^-10
Current in Amperes
Tube #2
Potassium
100° In Darkness
100° Potassium Illuminated
60
100
140
180

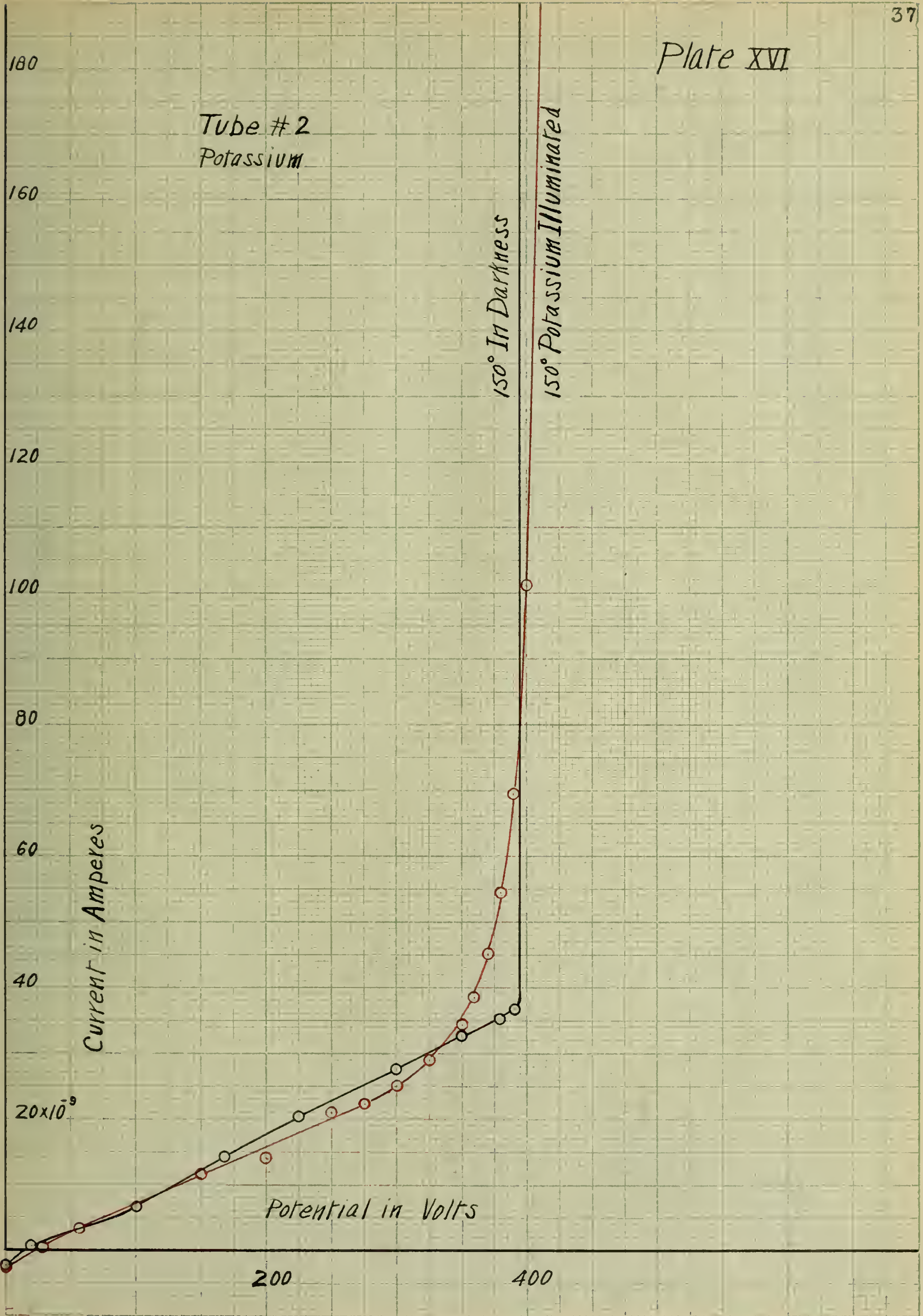
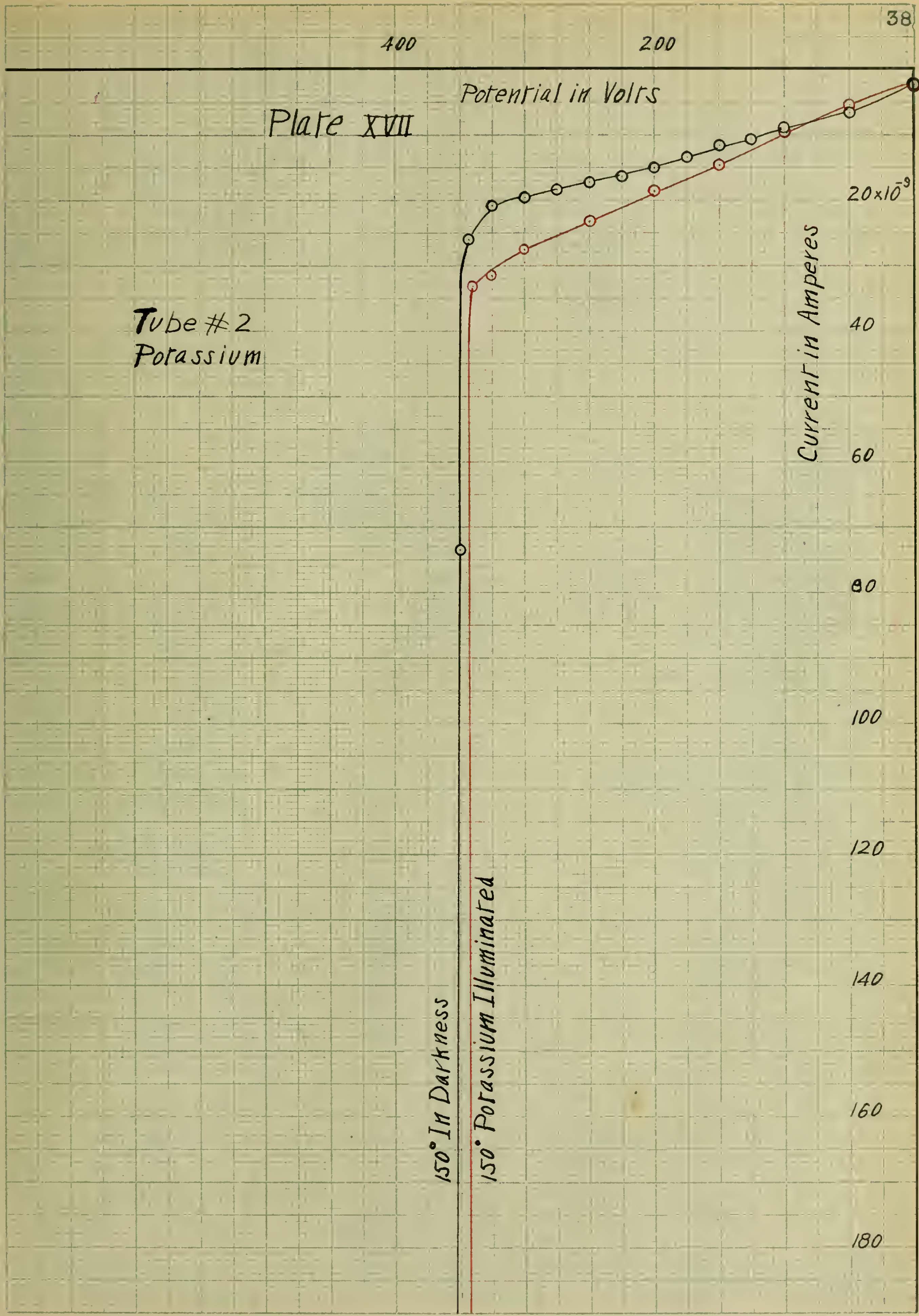


Plate XVI
Tube #2
Potassium
150° In Darkness
150° Potassium Illuminated
Current in Amperes
Potential in Volts
180
160
140
120
100
80
60
40
20×10⁻⁹
200
400


400
200
Potential in Volts
Plate XVII
20×10⁻⁹
Current in Amperes
Tube # 2
Potassium
40
60
80
100
120
140
160
180
150° In Darkness
150° Potassium Illuminated

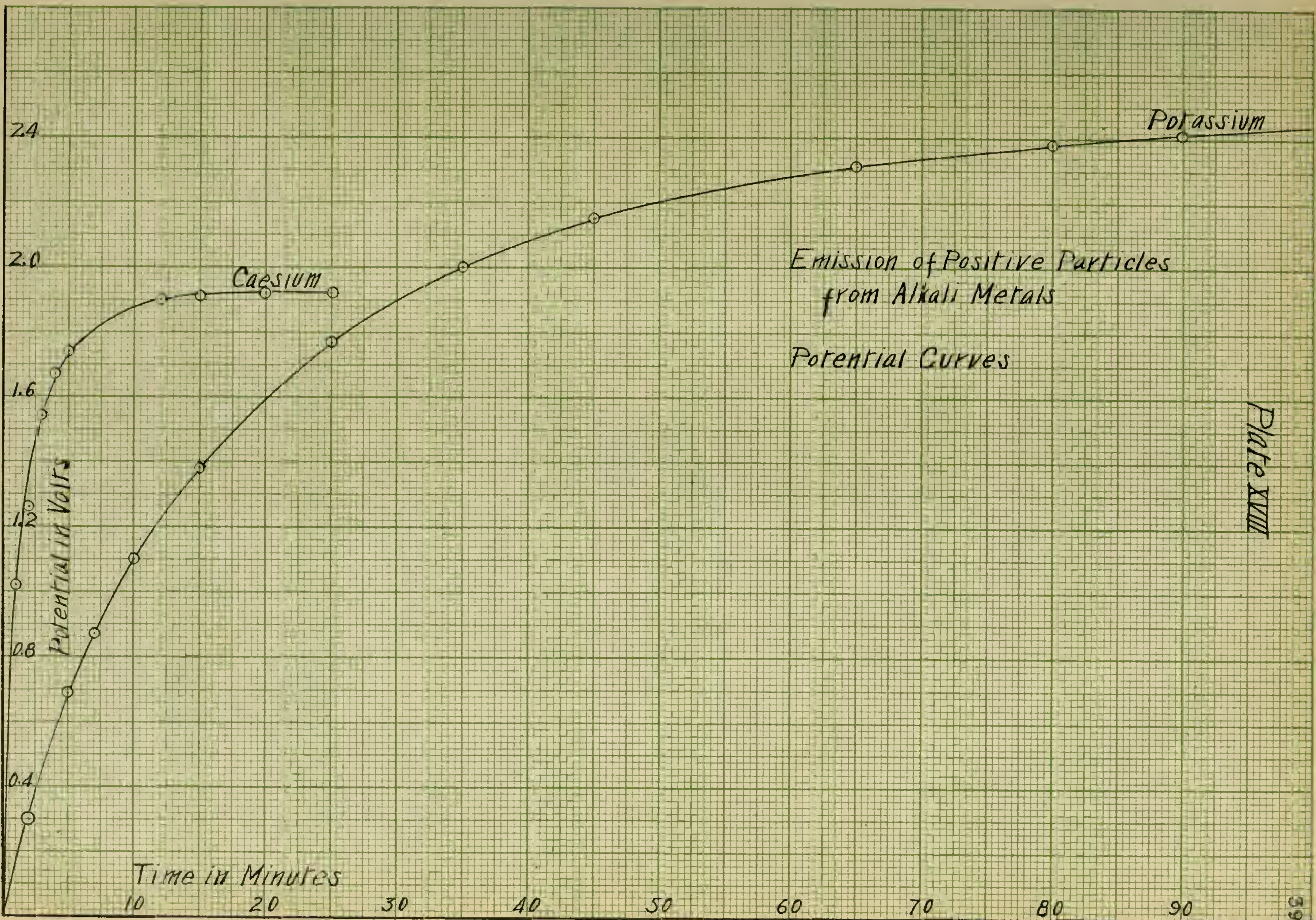


Plate XVIII
Emission of Positive Particles
from Alkali Metals
Potential Curves
Potassium
Caesium
Potential in Volts
Time in Minutes
2.4
2.0
1.6
1.2
0.8
0.4
10
20
30
40
50
60
70
80
90

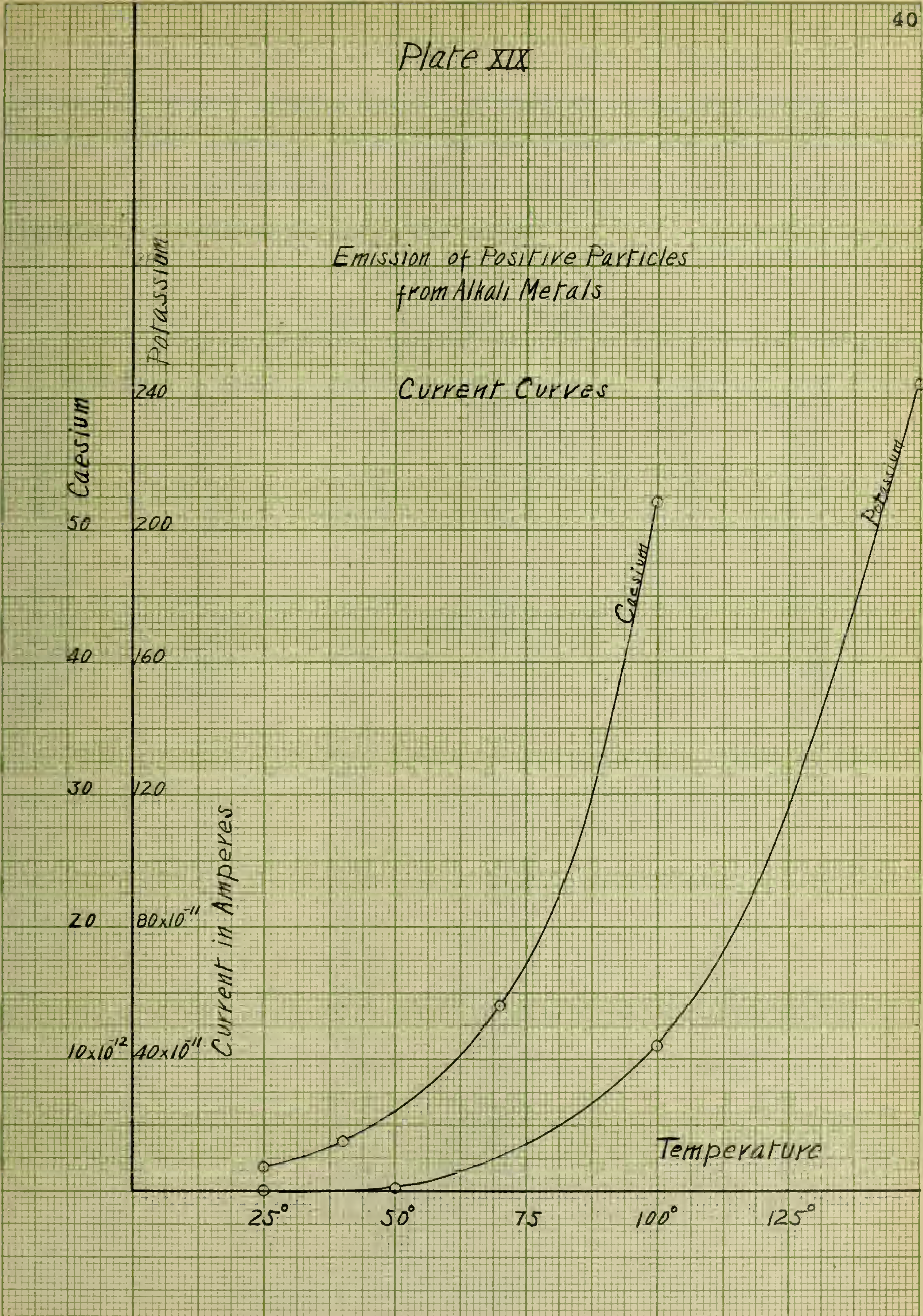


Plate XIX
Emission of Positive Particles
from Alkali Metals
Current Curves
Caesium
Potassium
Current in Amperes
Temperature
10x10^-12
20
30
40
50
40x10^-11
80x10^-11
120
160
200
240
25°
50°
75
100°
125°

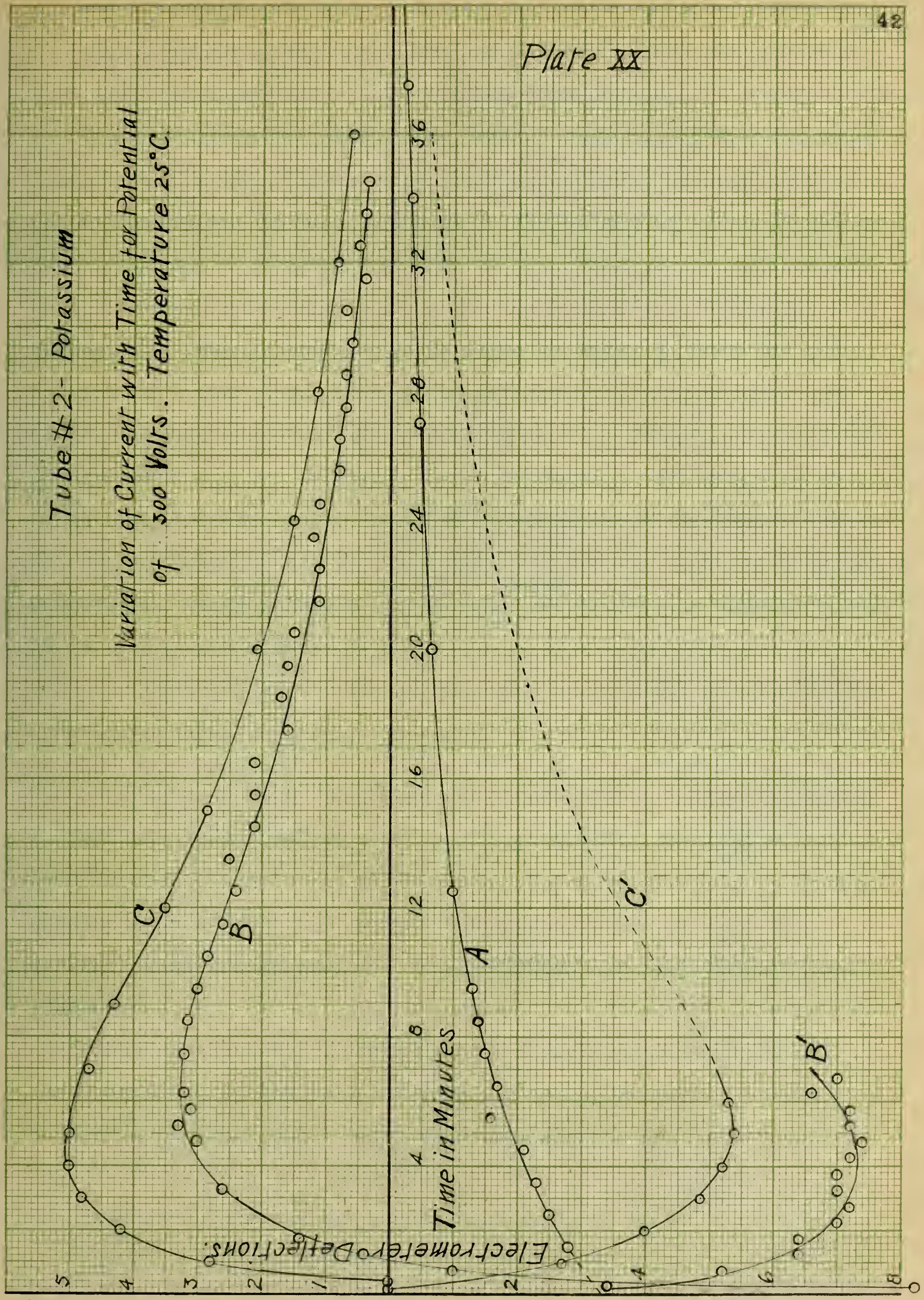
The second point of interest of this tube is that at 25° "in darkness", when a given potential is applied at <u>a</u>, the current occuring is not constant. In table VI and plate XX are given the data and curves which show how the current varies with the time for potentials of + 300 volts and - 300 volts.

Table VI

Variation of Current with Time. Temperature 25°.
(Time given in minutes, current in rate of electrometer deflection)

Potential 0 Volts		Potential +300 Volts.		Potential -300 volts	
Time	Current.	Time	Current	Time	Current
1.5	- 2.8	0.25	- 8.2	0.25	- 3.4
2.5	2.5	0.75	1.0	0.75	5.2
3.5	2.3	1.25	+ 0.4	1.25	6.4
4.5	2.1	1.75	1.4	1.75	6.4
5.5	1.6	3.25	2.2	2.25	7.0
6.5	1.7	4.75	3.0	2.75	7.2
7.5	1.5	5.25	3.3	3.25	7.0
8.5	1.4	5.75	3.1	3.75	7.0
9.5	1.3	6.25	3.2	4.25	7.2
12.5	1.02	7.5	3.2	4.75	7.4
20.0	0.66	8.5	3.15	5.25	7.2
27.5	0.46	9.5	3.0	5.75	7.2
32.5	0.32	10.5	2.85	6.25	6.6
37.5	0.26	11.5	2.6	6.75	7.0
		12.5	2.4		
		13.5	2.5		
		14.5	2.1		
		15.5	2.1		
		16.5	2.1		
		17.5	1.6		
		18.5	1.7		
		19.5	1.6		
		20.5	1.5		
		21.5	1.1		
		22.5	1.1		
		23.5	1.2		
		24.5	1.1		
		25.5	0.8		
		26.5	0.8		
		27.5	0.7		
		28.5	0.7		
		29.5	0.6		
		30.5	0.4		
		31.5	0.5		
		32.5	0.4		
		33.5	0.35		

Plate XX



NO. 346

Curve A, plate XX, shows how the current due to the positive particles given off from the potassium decreases as the charge builds up. The conditions for this curve are the same as for the potential curve of plate XIX. Electrode a is grounded and b is connected to the electrometer. In this curve as in the others of plate XX the current is given in terms of the rate of the electrometer deflections. When + 300 volts is applied at a and the key of the electrometer is opened, the rate of deflection is given by curve B. When the potential is - 300 volts curve B' is obtained. If the ordinates of A are subtracted algebraically from those of B and B', curves C and C' respectively are obtained. Data for curve B' could not be obtained for a time greater than 7 minutes as the deflections went off the scale. Curves C and C' are almost identical except in opposite directions. Hence it would appear that the difference between B and B' is due to the effect of A.

The equation of a curve of the type of C and C' is of the form

$$i = Ae^{-at} + Be^{-bt} + C.$$

The constants of this equation can be obtained by taking values of i for 5 different values of t and thus getting five equations with the five unkowns, A, B, C, a, b. The determination of these constants is a laborious process and was carried out only far enough to determine that all the constants are real and different from zero.

This equation then shows that there are three distinct effects occuring in the tube in addition to the current of curve A; a positive current which decreases according to the equation

$$i = Ae^{-at}$$

(2) a negative current decreasing according to

$$i = Be^{-bt}$$

(3) and a constant current given by

$$i = C.$$

For curve <u>C</u>' the component currents are in the opposite direction from those in curve <u>C</u>.

Curves <u>B</u> and <u>B</u>' are typical of all those taken for various potentials. For negative potentials of 560 volts or larger the initial current is positive; this decreases and is followed by a negative current which increases to a maximum and then decreases.

The features of the curves of plates XII - XVII to which attention will be called later are; (1) with the "potassium illuminated" all the curves obtained when a positive potential was applied at <u>a</u> show the characteristics of ionization curves, though saturation is not clearly marked; (2) the negative branch of the curve for "potassium illuminated" at 25° shows practically no current; (3) the abrupt bend away from the axis of abscissae in all the curves obtained when a negative potential was applied; (4) the curves "in darkness" and "potassium illuminated" very nearly coincide for the negative branches of the curves at 100°, plate XV, and for both the positive and negative branches of the curves at 150°, plates XVI and XVII

<u>Tube # 2</u>. <u>Caesium</u>. The observations in this series were carried out in the same manner as for tube # 2, potassium, except the temperatures used were 25°, 40°, 70° and 100°. The results are given in table VII and plates XXI - XXVI. The readiness with which caesium evaporates made it impossible to keep a constant surface for temperatures above the melting point. For this reason the curves are not very consistent.

The following features are worth noting; (1) the existence of a negative current when no field is applied, due to the emission of positive particles from the caesium; (2) the great increase in currents at 25° and 40° when the caesium is illuminated over those when the metal was in darkness; (3) the positive branches of the curves "caesium illuminated" at 25°, 40° and 70° are ionization curves.

Table VII

Tube # 2. Caesium

Temperature 25°

In Darkness		Caesium Illuminated	
Potential in Volts	Current in Amperes	Potential in Volts	Current in Amperes
0	-1.83×10^{-12}	0	$+0.58\times10^{-11}$
+ 100	+ 0.763	+ 57	8.53
200	1.502	100	10.56
300	2.26	200	13.08
400	3.34	300	15.4
500	4.51	400	16.3
600	6.44	500	18.0
700	9.35	600	20.2
800	11.27	700	21.5
900	13.4	800	22.8
1000	16.85	900	24.1
1100	19.6	1000	25.4
1200	23.85	1640	192.0
1300	29.2		
1400	33.5	- 100	- 0.704
1600	38.3	200	0.963
1650	40.2	300	1.11
		400	1.26
- 100	- 2.59	500	1.295
200	3.35	600	1.705
300	4.26	700	1.89
400	5.47	800	2.295
500	7.08	900	2.67
600	8.52	1000	3.37
700	10.75	1100	3.74
800	13.6	1200	4.77
900	16.4	1300	5.74
1000	20.2	1400	7.03
1100	24.2	1500	10.65
1200	30.1	1600	11.5
1300	36.0	1650	13.2
1400	47.0		

Table VII (Con'd)

Temperature 40°

In Darkness		Caesium Illuminated	
Potential in Volts	Current in Amperes	Potential in Volts	Current in Amperes
0	-5.94×10^{-12}	0	$+0.222\times10^{-11}$
+100	2.58	+ 10	14.2
200	1.29	88	23.1
300	1.4	410	83.7
400	+ 6.87	500	543.0
500	16.8		
600	22.6		
625	60.2		
650	off scale		
-100	-7.76	- 12	- 4.82
200	9.9	57	6.33
300	19.5	100	8.15
400	41.2	200	8.7
600	837.0	300	11.85
		366	25.6
		550	83.7
		600	234.0

Temperature 70°

0	-14.0×10^{-12}	+ 0	-0.036×10^{-10}
+100	1.2	+ 12	+ o.113
200	+ 15.6	67	1.64
300	78.8	100	1.88
370	232.0	200	2.48
432	8370.0	300	3.35
550	16750.0	400	83.7
600	46000.0	500	167.5
		595	2010.0
-100	-0.293×10^{-10}	- 11	- 0.316
200	0.58	68	0.464
300	1.7	100	0.547
321	2.53	170	0.788
420	217.0	197	2.53
500	292.0	300	14.2
600	456.8	400	25.05
		500	201.0
		600	850.0

Table VII (Con'd)

Temperature 100°

In Darkness		Caesium Illuminated	
Potential in Volts	Current in Amperes	Potential in Volts	Current in Amperes
0	$-\ 0.5 \times 10^{-10}$	0	$-\ 0.248 \times 10^{-10}$
+ 100	+ 0.1	+ 69	1.068
200	0.9	100	1.43
300	2.64	190	2.68
400	10.05	300	12.55
500	23.4	400	20.05
600	134.0	500	38.2
665	655.0	600	41.8
		800	100.5
- 100	- 1.09	1000	309.0
200	2.25	1200	577.0
300	3.35	1400	928.0
400	10.9	1600	1420.0
500	25.01		
600	45.2	- 76	- 1.145
700	75.3	100	1.6
825	250.5	200	4.18
900	301.0	300	8.37
1000	535.0	400	16.75
1100	661.0	600	67.0
1200	765.0	800	159.0
1300	887.0	1000	259.0
1500	1210.0	1200	385.0
		1400	678.0
		1600	1005.0

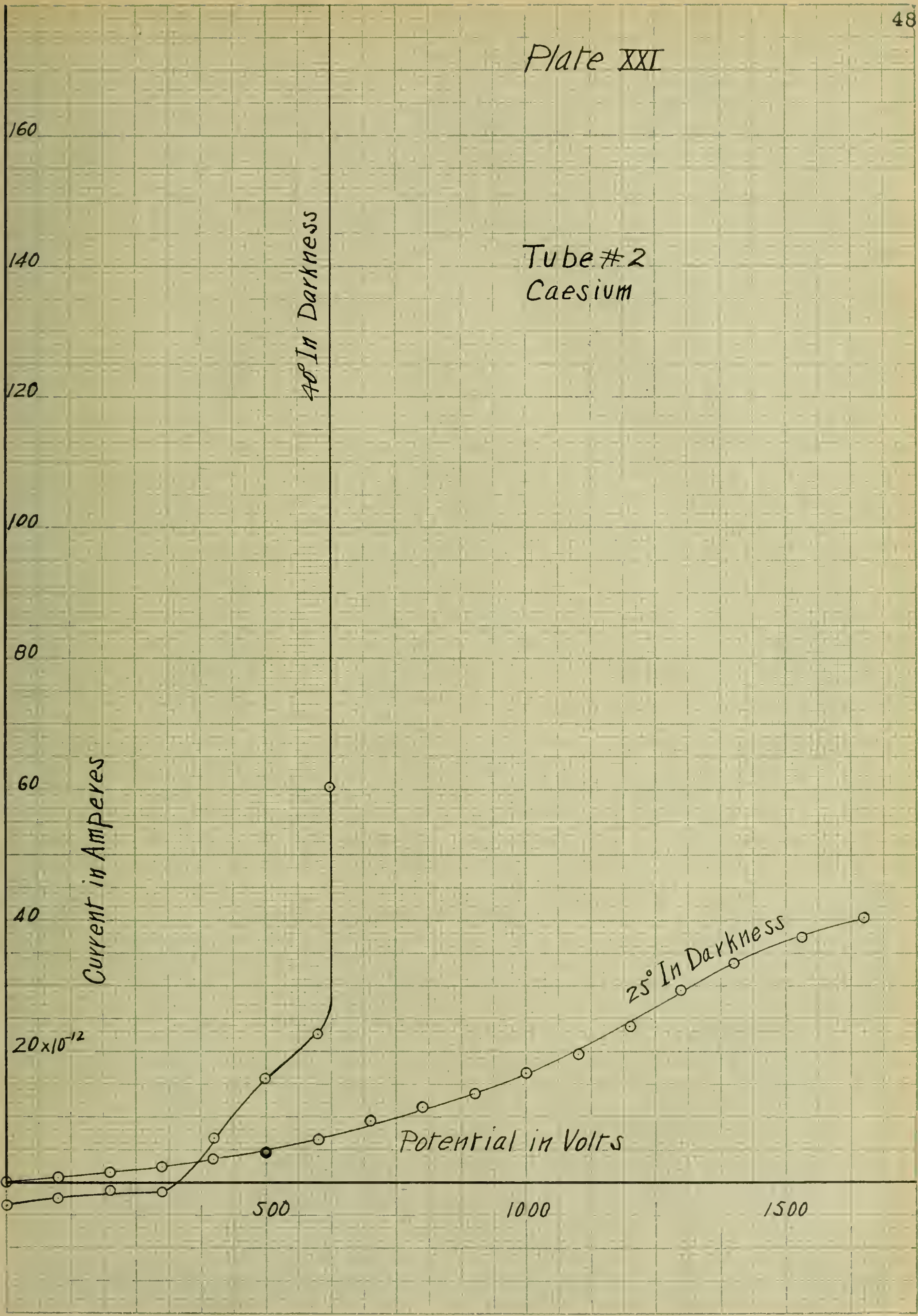
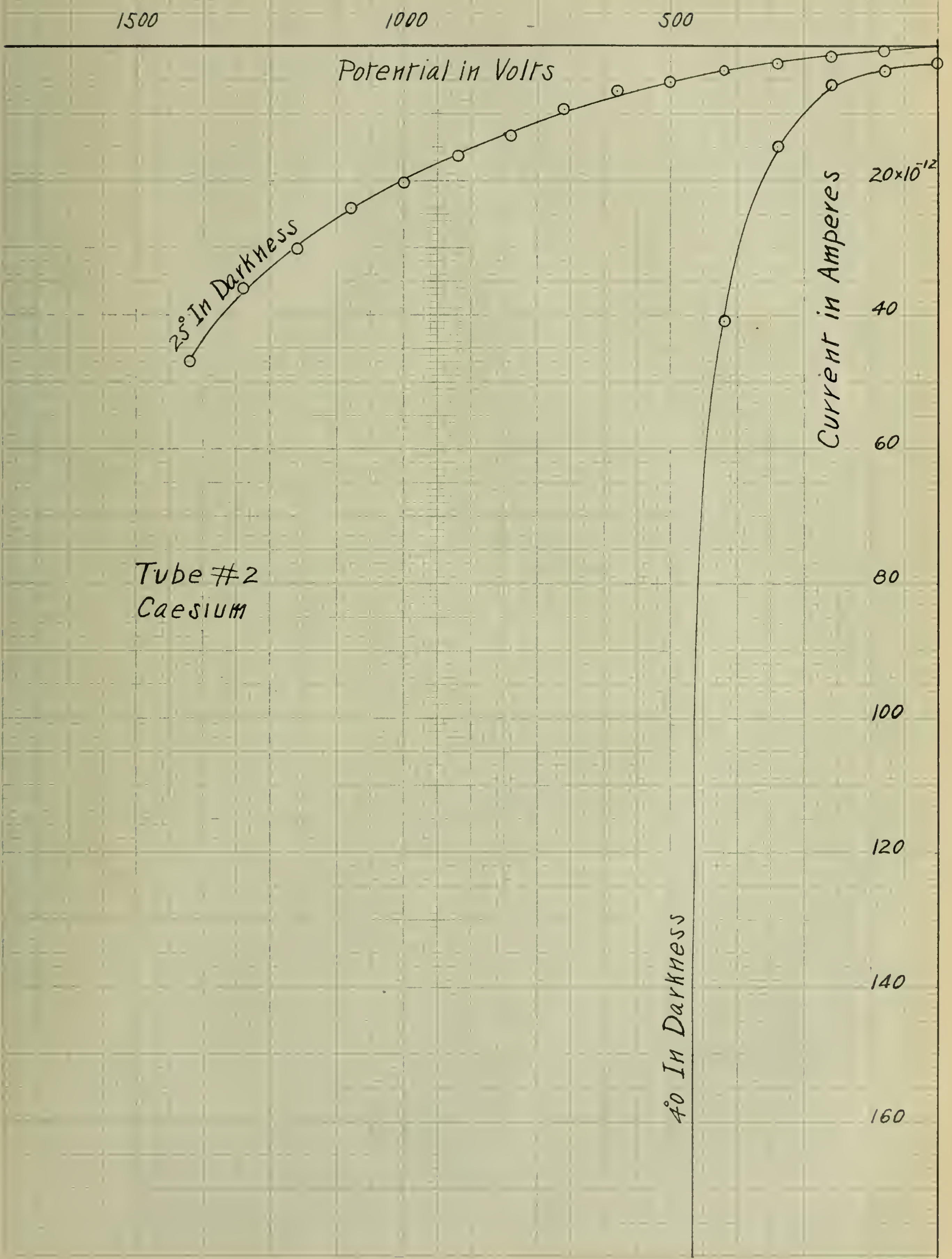


Plate XXI
Tube #2
Caesium
40° In Darkness
25° In Darkness
Current in Amperes
Potential in Volts
160
140
120
100
80
60
40
20x10⁻¹²
500
1000
1500

Plate XXII


1500
1000
500
Potential in Volts
25° In Darkness
4° In Darkness
Current in Amperes
20×10⁻¹²
40
60
80
100
120
140
160
Tube #2
Caesium

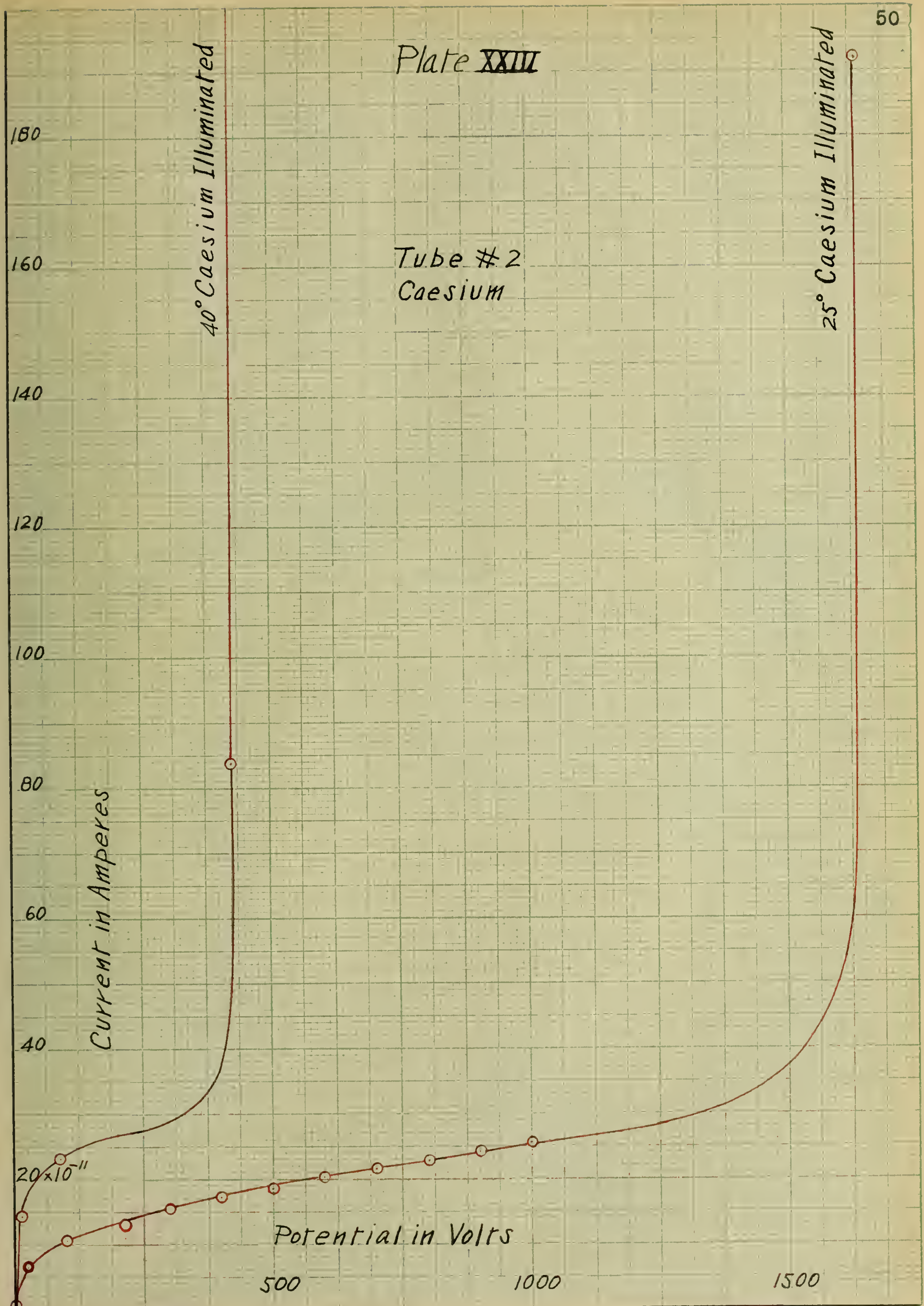


Plate XXIII
Tube #2
Caesium
40° Caesium Illuminated
25° Caesium Illuminated
Current in Amperes
Potential in Volts
20×10⁻¹¹
40
60
80
100
120
140
160
180
500
1000
1500

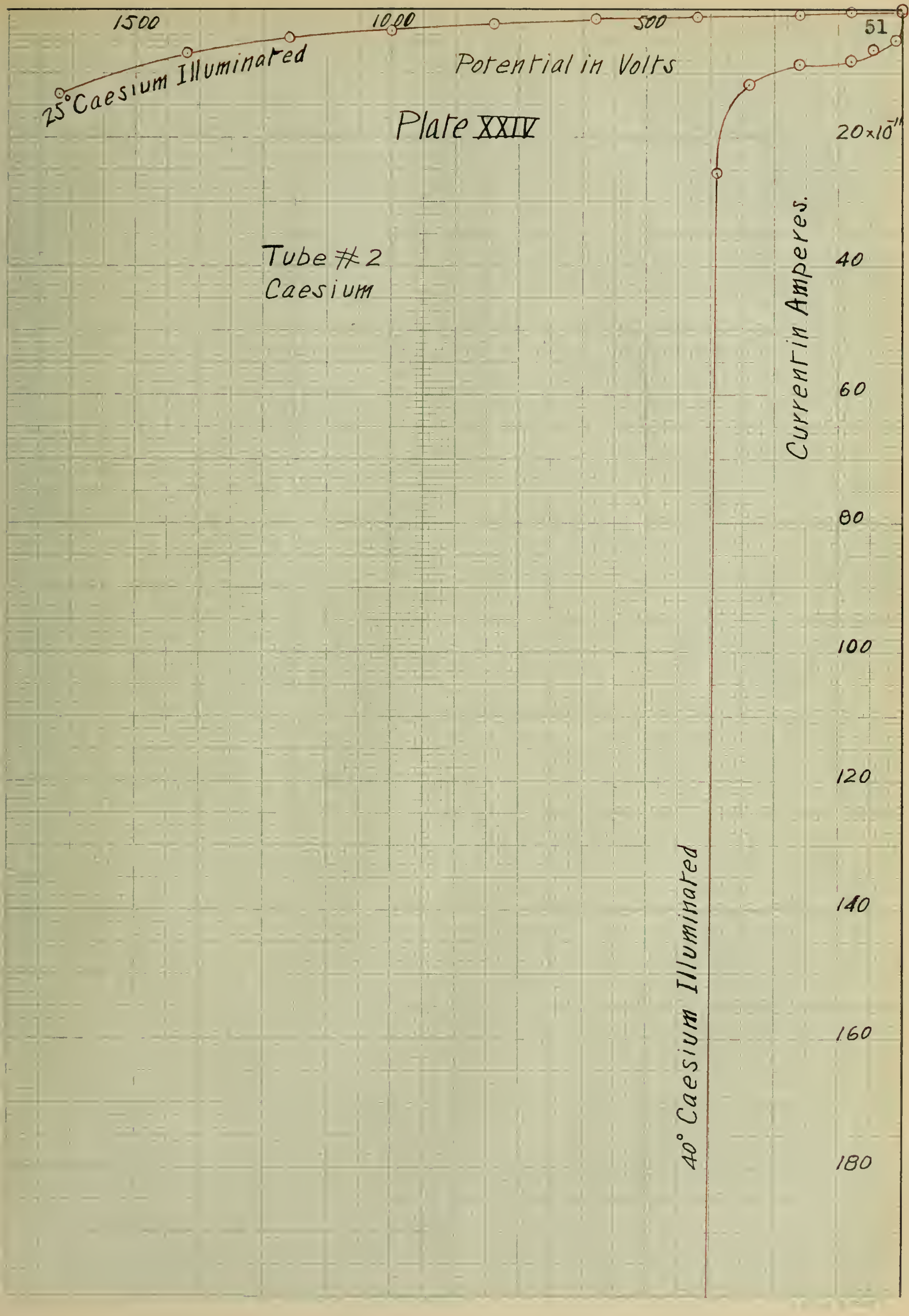


Plate XXIV
Tube # 2
Caesium
Potential in Volts
1500
1000
500
25° Caesium Illuminated
40° Caesium Illuminated
Current in Amperes.
20×10⁻¹¹
40
60
80
100
120
140
160
180

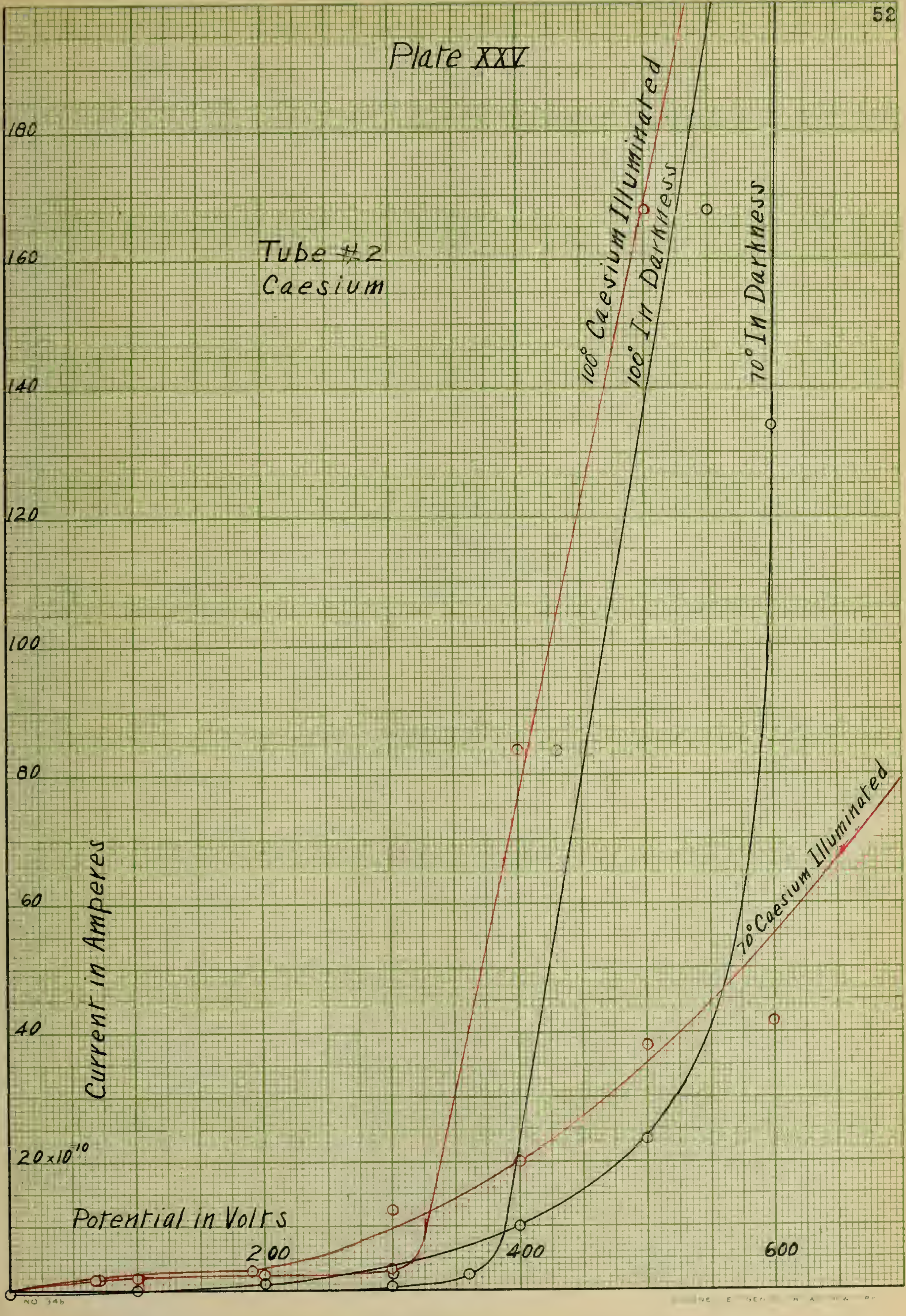
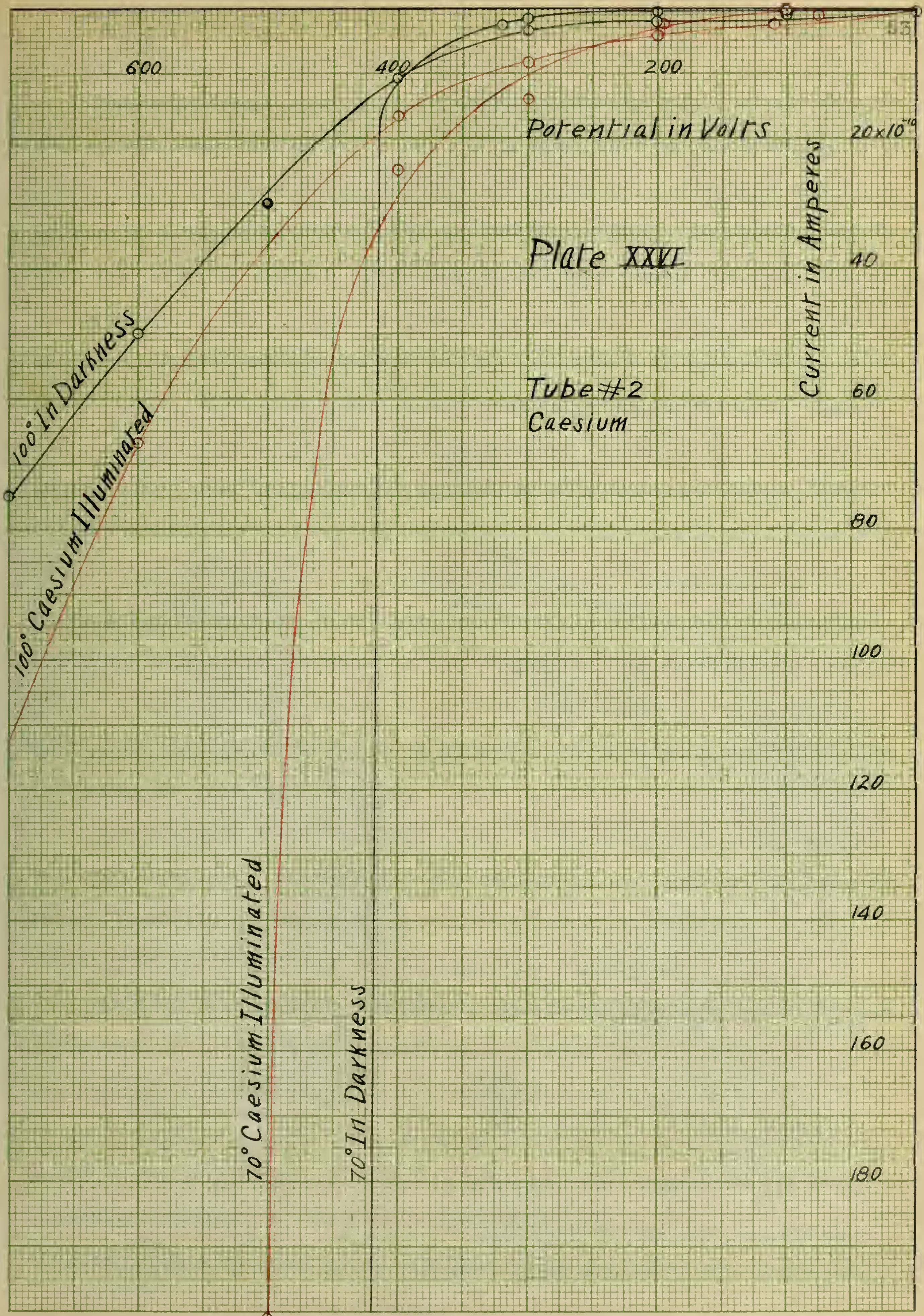


Plate XXV
Tube #2
Caesium
100° Caesium Illuminated
100° In Darkness
70° In Darkness
70° Caesium Illuminated
Current in Amperes
Potential in Volts
180
160
140
120
100
80
60
40
20×10⁻¹⁰
200
400
600



600
400
200
Potential in Volts
20x10⁻¹⁰
Current in Amperes
Plate XXVI
40
60
80
100
120
140
160
180
Tube #2
Caesium
100° In Darkness
100° Caesium Illuminated
70° Caesium Illuminated
70° In Darkness

NO 346

Discussion of Results

The experiment with tube # 1 with potassium vapor alone between the electrodes, that is with the solid potassium in bulb c (fig.1), shows that there is nothing of the character of a spontaneous ionization at a temperature as high as 75? No conductivity of the usual type was observed when a potential up to 1700 volts was applied. At a temperature of 100° when the potential is gradually increased there is a luminous discharge at 700 volts. But there is no current before this occurs. The abruptness of the discharge indicates that there are no ions present until produced at this instant. At this temperature, 100°, the velocity of agitation is relatively large. Some molecule acquires sufficient velocity, so that when a collision with another molecule occurs the electron system of the atom is put in such an unstable condition that the electric force due to the 700 volts is sufficient to drag an electron from the atom and ionization occurs. The ions thus produced acquire sufficient velocity under the action of the electric field to produce ionization by collision and the luminous discharge occurs.

The absence of spontaneous ionization is further verified by the fact that when in tube # 1 the potassium was introduced into the tube so as to lie between the electrodes no conductivity of the usual type occured until the temperature was raised to 100°.

Woodrow found that the alkali metals in the dark gave off positive particles and that the current arising therefrom increased with the temperature according to the relation

$$i = aT\, e^{-\frac{b}{T}}$$

where a and b are constants and T the absolute temperature. (See curves of plate XIX). If this correctly represents the phenomenon then the velocity with which the particles are shot off increases

with the temperature. This will be used as a basis for explaining the peculiarities of the curves of plates X and XI to which attention was called on page 23.

The curve for 100° "in darkness" is a straight line for potentials up to 1600 volts. It does not seem reasonable to assume that this is a portion of an ionization curve or saturation would be reached before 1600 volts. Sinee positive particles are given off from the liquid potassium at this temperature in some considerable numbers, we may assume that from the surplus of electrons left in the metal some will be given off under the action of the field between the electrodes. When equilibrium is reached the same number of positive and negative particles will be given off and there will be a steady current. Since in all probability the positive ions are atoms of potassium, potassium will be deposited on electrode b. (fig. 1). The number of positive and negative particles given off will increase with the field, and if the relation is a linear one the curve is explained.

After this curve is taken with the positive potential, the curve with the negative potential is taken at the same temperature. Now with the field in this opposite direction to what it was formerly positive particles will be given off from the layer of potassium on electrode b in addition to the positive and negative particles given off from the potassium in the tube. The direction of the field will facilitate the natural tendency of the potassium to give off positive particles. This accounts for the fact that in the negative branch of the curve for 100° "in darkness" , plate XI the currents are a little larger than in the positive branch. Furthermore at 875 volts there is an abrupt bend in the curve, showing ionization by collision. At this potential the positive particles acquire suf-

ficient velocity to ionize the vapor. And increase of ionization is very rapid when positive ions begin to produce ionization by collision.

For 150° the order of taking observations was the same as for 100° and this would result in a greater deposit of potassium on electrode b. The negative branch of the curve "in darkness" becomes parallel to the current axis for a lower potential than the positive branch. (See plates X and XI). And this is accounted for by the fact that positive particles are given off from electrode b when the field is in this direction.

Attention has been called to the fact that for 25°, 50° and 100° the positive branches of the curves for "potassium illuminated" give larger vales for the currents in the linear portions of the curves than do the negative branches. This can be explained also by assuming that there is some potassium deposited on electrode b. For when the direction of the field is from a to b (fig. 1) under the action of reflected light electrons will be given off, while they will not be given off so readily when the field is from b to a. The curve for 150° "potassium illuminated" differs from those of lower temperatures by having larger currents in the negative portion. This is probably due to the fact that at this temperature the positive particles are given off very much more readily and have sufficient velocity to produce ionization with a lower field acting.

Another peculiarity of these curves which indicates the deposit of potassium on electrode b is that with no field a negative current is observed at 100° and 150°. This is the only feasible explanation of this phenomenon.

Attention previously has been called to the fact that the curves with tube #2 potassium, plates XII - XVII, show the characteristic

features of ionization curves, viz.; (1) a straight line where the current obeys Ohm's law, followed by a bending toward the x-axis; (2) a portion parallel to the x-axis where saturation occurs; (3) a rapid rise away from the x-axis where ionization by collision begins. The curves obtained differ from the ionization curve above described in that at no point does the curve become parallel to the x-axis. This is due to the source of ions. In order to have a portion of the curve parallel to the x-axis, the source of ions must be such that the rate of producing these primary ions is constant. This is the case where the gas is ionized by Röntgen rays or a radioactive substance. In this experiment the source of ions is the photo-electric action of the potassium, and the rate production increases with the potential applied. This accounts for the straight line portion of the curve seen in the curves of plate XII. The point where the curve begins to bend away from the straight corresponds to the potential where ionization by collision begins. In the curves taken at 100° and 150° (plates XIV and XVI) the straight line part of the curve is not so apparent because at these temperatures because ionization by collisions begins at a lower potential.

The statements given above for the curves obtained with potassium hold for those with caesium taken at 25° and 40°. (See plate XXIII).

In plate XIII the negative branch of the curve taken at 25° with the potassium illuminated shows practically no current. This is what would be expected; for with the field in that direction no electrons would be given off. Any current that occurs must be due to positive particles. It is reasonable to expect that if a higher voltage had been applied there would have occured an abrupt bend as in the curves for 50°. These bends occur where the positive

particles acquire sufficient velocity to produce ionization by collision. Reference to the table IV will show that for potentials lower than 300 volts there are currents, but too small to be represented in the curves. We might infer from the fact that,when light is incident on the metal,this bend occurs at a lower potential that light shinning through the vapor renders it more easily ionized.

The close agreement of the curves in plate XV for"in darkness" and "potassium illuminated" shows that the source of ions must be the positive particles whose release from the potassium is not effected by the action of light. The same can be said for the curves at 150°. plate XVII.

In order to compare the conductivity for different temperatures potentials, and positions of the potassiumin the tube , table VII has been prepared.

Table VIII

(Potential given in volts, current in amperes)

Potential	Potassium in Bulb c.	Potassium between Electrodes.	Potassium at Electrode b.
		Temperature 25°	
0	0.0	0.0	- 0.283$\times10^{-12}$
+ 300	- 0.058$\times10^{-12}$	- 0.092$\times10^{-12}$	- 0.71
600	- 0.116	- c.18	- 2.1
900	- o.172	- 0.3	- 2.1
1200	- 0.223	- 0.4	- 2.1
1500	- 0.268	- 0.5	- 2.1
		Temperature 50°	
0	0.0	0.0	- 5.9 $\times10^{-12}$
+ 300	- 0.774$\times10^{-12}$	- o.57 $\times10^{-12}$	- 3.8
600	- 1.5	- 1.23	+ off scale
900	- 2.27	- 1.72	
1200	- 3.14	- 2.36	
1500	- 4.3	- 3.00	
		Temperature 100°	
0		- 0.243$\times10^{-12}$	-440.0 $\times10^{-12}$
+ 300		+ 0.85	+156.0
600		+ 1.9	off scale
900		+ 3.2	
1200		+ 4.0	
1500		+ 5.01	
		Temperature 150°	
0		- 5.6 $\times10^{-12}$	-2440.0$\times10^{-12}$
+ 300		+14.62	+ 27600.0
600		+25.3	off scale

Table IX shows how the currents obtained in tube # 2 with electrode b of potassium vary with the temperature. By plotting temperatures as abscissae and currents as ordinates the relation between the temperature and current can be better seen than from the curves given above.

Table IX.

Potential 0 volts.

Temperature	Current In Darkness	Current Potassium Illuminated
25°	- 0.0283×10^{-11}	+ 0.075×10^{-10}
50°	- 0.59	- 0.242
100°	- 44.0	- 4.3
150°	-244.0	- 21.0

Potential + 100 volts.

Temperature	Current In Darkness	Current Potassium Illuminated
25°	- 0.035	+ 3.2
50°	- 0.556	+ 2.6
100°	- 22.0	+ 2.3
150°	+670.0	+ 70.0

Potential + 200 volts

Temperature	Current In Darkness	Current Potassium Illuminated
25°	- 0.056	+ 5.0
50°	- 0.47	+ 5.0
100°	- 1.56	+ 9.6
150°	+1780.0	+ 158.0

Potential + 300 volts

Temperature	Current In Darkness	Current Potassium Illuminated
25°	- 0.071	+ 6.5
50°	- 0.38	+ 10.5
100°	+ 15.0	+ 23.8
150°	+2760.0	+ 250.0

Potential + 400 volts

Temperature	Current In Darkness	Current Potassium Illuminated
25°	- 0.101	+ 8.7
50°	- 0.4	+ 28.5
100°	+ 30.0	+ 58.5
150°	off scale	+1010.0

[illegible]

[illegible]

[illegible]	[illegible]	[illegible]

[illegible]

[illegible]	[illegible]	[illegible]

[illegible]

[illegible]	[illegible]	[illegible]

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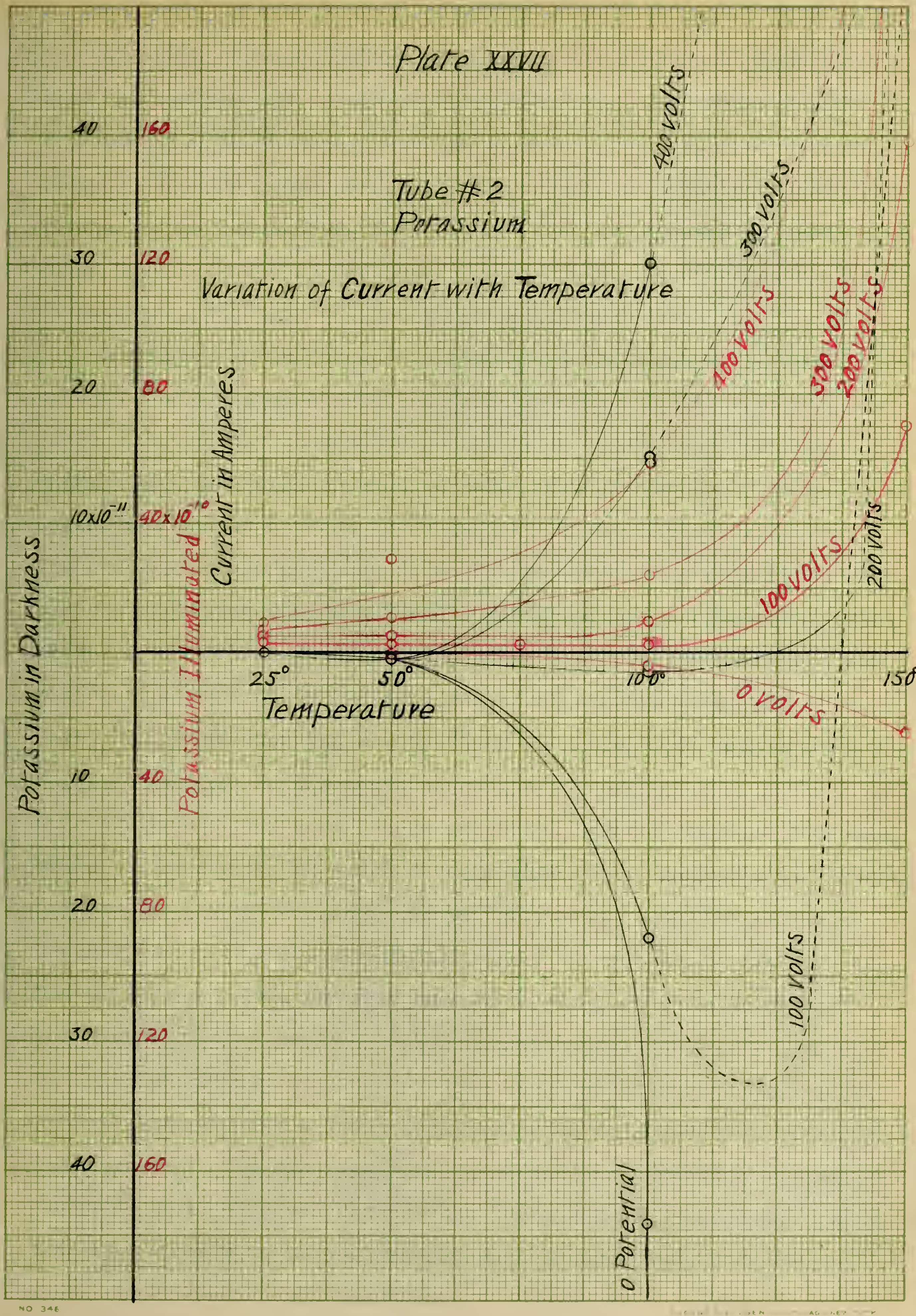

Plate XXVII
Tube # 2
Potassium
Variation of Current with Temperature
Current in Amperes.
Potassium in Darkness
Potassium Illuminated
Temperature
40
160
30
120
20
80
10x10⁻¹¹
40x10⁻¹⁰
10
40
20
80
30
120
40
160
25°
50°
100°
150
400 volts
300 volts
400 volts
300 volts
200 volts
100 volts
200 volts
0 volts
100 volts
0 Potential
NO 346

The data of table IX are plotted in the curves of plate XXVII. Here, as before, the curves in black represent the currents with the potassium in darkness, and the curves in red with the potassium illuminated. The broken lines indicate that the exact course of the curves is not determined. The ordinates of the red curves have 40 times the value of the ordinates of the black. The direction of the electrical field is from a to b. (fig.2).

The black curve for zero potential shows there is a negative current for all temperatures. When a potential of 100 volts is applied this current is decreased, and between 100° and 150° there is a reversal. The table shows a positive current for 150° As a stronger field is applied the negative current becomes less for temperatures above 50°. But it is rather surprising that at 50° the current is nearly the same for all field strengths. Since the positive current is due to electrons given off from the potassium these curves show that up to 50° very few electrons are given off in the dark, but above this temperature they are given off readily when a field is applied in the right direction.

If the red curve for zero potential were plotted on the same scale as the black, it would be seen that there is little difference between the two as the table shows. This means that the electron current due to the photo-electric effect is very small compared to the emission of positive particles from the potassium at higher temperatures. The greatest relative difference between the two effects is at 25°. At this temperature when the light is applied the current changes from a small negative value to a positive value 25 times greater. But for higher temperatures the resulting current is negative both with and without the light and the difference between the two currents is only a few percent. However when a field is

applied in the direction from a to b then the electron current becomes predominant.

Quantitative Results.

Ratio of the Number of Electrons Given off to the Number of Atoms Present. From the electron current occuring when the potassium is illuminated either without a potential applied or with a potential, the number of electrons leaving the surface of the alkali metal per second can be computed and compared with the number of atoms in the active layer. At 25° the negative current for potassium in darkness with zero potential is 0.283×10^{-12} amperes. And the positive current when the potassium is illuminated is 7.5×10^{-12} amperes. Since the positive current must be the difference between the current due to the electrons and that due to the positive particles, the current of electrons must be

$$7.5\times10^{-12} + 0.283\times10^{-12} = 7.783\times10^{-12}\text{amperes}$$

$$7.78\times10^{-12}\text{amp.} = 7.78\times10^{-13} \text{ e.m. units}$$

The number of electrons reaching the electrode per second is

$$\frac{7.78\times10^{-13}}{1.55\times10^{-20}} = 5.02\times10^{7}$$

where 1.55×10^{-20} is the value of e in electromagnetic units.

The potassium was in the shape of a disk with a very nearly flat surface and a radius of about 1 cm.

Area of potassium = $1^2 = 3.1416$ cm^2.

Diameter of potassium atom = 4.74×10^{-8}cm.

Cross-sectional area occupied by one potassium atom is

$$(4.74\times10^{-8})^2 = 2.25\times10^{-15}\text{cm}^2.$$

Number of atoms in one layer = $\frac{3.1416}{2.25\times10^{-15}} = 1.397\times10^{15}$

[illegible]

Ladenburg[1] has foundthat the thickness of the layer of metal effected by light is about 10^{-4}cm. Hence the number of layers of atoms of potassium in the active layer of the metal is given by

$$\frac{10^{-4}}{4.74\times10^{-8}} = 2.11\times10^{3}$$

The total number atoms in the active layer is

$$1.397\times10^{15} \times 2.11\times10^{3} = 2.95\times10^{18}$$

Ratio of number of atoms to number of electrons given off per second is

$$\frac{2.95\times10^{18}}{5.02\times10^{7}} = 5.88\times10^{10}$$

That is, one atom out of 5.88×10^{10} gives out one electron per second. At this rate it would require 5.88×10^{10} seconds or 1860 years for each atom to give out one electron. Of course the electron current can be considerable increased by using a more intense light and one of shorter wave length. And then the ratio between the number of atoms and the number of electrons given off will be much decreased. But this computation serves to emphasize the fact that the number of atoms effected is exceedingly small. This may be due to one of two causes, or possibly to both: (1) only a very few of the atoms are in condition to give out electrons under the influence of light; (2) Light has a structure, and the energy is not uniformly distributed over the light wave front, but is concentrated along certain lines as suggested by the theory of J.J. Thomson[2] and amplified by Kunz[3]. In this investigation there is some evidence in favor of the first explanation. A comparison of the curves for "potassium illuminated" and "in darkness" in plates XII, XIV and XVI will show that as the temperature increases the effect of light on

1 Ann. der Phys. 12, p.558, 1903
2 Proc. of Camb. Phil. Soc. 14, pt.4, p.41, 1908
3 Phys. Rev. 29, p.212, 1909.

the current becomes less and less, until at 150° the curves for "potassium illuminated" and "in darkness" almost coincide. That is at this temperature electrons are given off just as readily without light as with it when an electric field is applied, or the photo-electric action at this temperature is practically zero. Hence it appears that the electron current depends more upon the condition of the metal than on the incident light. If the number of electrons given off depended alone on the structure of light, the electron current should be much larger with light than without light for all temperatures.

At 150° with + 100 volts potential the current is about 1000 times larger than at 25° and with zero potential. But even with this current the ratio between the number of atoms and the number of electrons given off is a large one, 5.88×10^7. So that even at this temperature the number of atoms in condition to give off electrons is small

Estimate of the Maximum Vapor Pressure Possible of Potassium. When light is incident on a metal the electrons are given off with a velocity which can be obtained by the relation

$$Pe = 1/2mv^2$$

where e is the charge of the electron and P the maximum positive potential assumed by the metal in the photo-electric action. The maximum velocity of the electrons from potassium in this work when zero potential was applied is due to the shortest wave length of visible light, about 4200. D.W. Cornelius in this laboratory found the velocity due to this wave length to be 6.21×10^7 cm. per second. When there is an electric field acting the velocity of the electrons increases beyond the initial velocity until the electron has sufficient velocity to produce an ion by collision. This relation is expressed by

$$W = Eel + 1/2mv^2$$

where W is the energy required to produce an ion, E the electric field, e the elementary electrical charge, m the mass of the electron, v the initial velocity and l the distance from the surface of the metal that the electron must go to gain sufficient velocity to produce ionization. The value of E can be taken from the curve at the point of departure from a straight line. From the curve for 25° plate XII, we find the potential corresponding to this point of departure to be 350 volts. As the electrodes were 2 cm. apart, the value of E is

$$\frac{350}{2} = 175 \text{ volts per cm.}$$

$$E = \frac{175}{300} = 0.583 \text{ e.s. units per cm.}$$

$$e = 4.65 \times 10^{-10}$$

$$m = 8.7 \times 10^{-28}$$

$$v = 6.21 \times 10^{7}$$

The value of W is taken at 1.58×10^{-11} ergs, which is the value obtained by Bishop[1] for hydrogen and also by Kemp in this laboratory. So far as has been investigated this value does not vary very much for different gases, so it will be assumed that it is a reasonable value for potassium vapor.

$$l = \frac{W - 1/2\, mv^2}{Ee} = \frac{1.58\times10^{-11} - \frac{8.7\times10^{-28}(6.21\times10^{7})^2}{2}}{5.83\times10^{-1} \times 4.65\times10^{-10}}$$

$$= \frac{1.58\times10^{-11} - 0.169\times10^{-11}}{2.71\times10^{-10}}$$

$$= 5.2 \times 10^{-2} \text{ cm.}$$

Now the mean free path of the molecules of potassium vapor must be at least this great or there could be no ionization by collision

1 Phys. Rev. 33, p.325, 1911.

at this field strength. Assuming this to be the minimum mean free path we can calculate the maximum number of molecules per cm^3. The mean free path is given by

$$l = \frac{1}{\sqrt{2}\pi n \sigma^2}$$

where $\underline{n}$ is the number of molecules per cubic centimeter and is the diameter of the molecule. We have then

$$n = \frac{1}{\sqrt{2}\pi l \sigma^2} = \frac{1.}{2 \times 5.2\times10^{-2}(4.74\times10^{-8})^2}$$

$$= 1.925\times10^{15}$$

We may assume that at the temperature and pressure existing in the tube the potassium vapor acts as a perfect gas and so compute the pressure from

$$P = \frac{P_o T n}{T_o n_o}$$

where $\underline{P_o}$ = 760 mm. pressure, T_o = 273°, n_o the number of molecules in a cubic centimeter of gas at standard conditions and is equal to 2.72×10^{19}, T the absolue temperature of the vapor and $\underline{n}$ the number of molecules of the vapor per cm^3. Hence

$$P = \frac{760 \times 298 \times 1.925\times10^{15}}{273 \times 2.72\times10^{19}}$$

$$= 0.0587 \text{ mm.}$$

This is of the order of magnitude that would be expected.

This problem of the conductivity in alkali vapors is by no means solved. One very important feature which should be investigated is the effect of ultra-violet light . Does ultra-violet light ionize the vapor? And is there ionization from the electrons given off from the metal?

From the data some prediction can be made on this last point.

Taking the energy necessary to produce an ion to be 1.58×10^{-11} ergs we can compute the velocity that an electron should have to produce ions by collision.

$$W = 1/2\ mv^2$$

$$v^2 = \frac{2W}{m} = \frac{2 \times 1.58\times10^{-11}}{8.7\times10^{-28}} = 3.63\times10^{16}$$

$$v = 1.9 \times 10^8 \text{ cm per second.}$$

If we assume that the velocity of the electrons in the photo-electric effect varies inversely as the wave length, we have

$$v_2 = v_1\frac{\lambda_1}{\lambda_2}$$

Taking $v_1 = 6.21\times10^7$ for $\lambda_1 = 4200$ and $\lambda_2 = 2000$, which is about the shortest wave length which can be obtained with a quartz spectrometer, we find

$$v_2 = 6.21\times10^7\ \frac{4200}{2000}$$
$$= 1.304 \times 10^8$$

This is less than the value 1.9×10^8 computed above. But it is of the same order of magnitude and if the minimum energy to produce an ion is less than 1.58×10^{-11} ergs, it is entirely possible for the electrons set free from potassium by the action of the short wave lengths of ultra-violet light to produce ionization by collision.

In some other work carried on by the author a potential of 5.85 volts was obtained from potassium illuminated by 2100. This gives a velocity of 1.445×10^8 cm. per second which is some nearer the critical velocity to produce ionization.

These values would indicate that it would be well worth while to investigate this point.

Conclusion.

1. This investigation has shown that when potassium vapor alone is between the electrodes of a tube there is no conductivity of the usual type at 25° and 50°; at 100° with a potential of 700 volts there is a current arising from ionization by the electric field. Hence there is nothing of the character of a spontaneous ionization.

2. When potassium was present in the tube but not in contact with the electrodes there is no conductivity of the usual type at 25° and 50°. At 100° there is a current due to particles given off from the potassium.

3. In a tube with two similar electrodes exhausted to the best degree possible there is a current of the order 10^{-13} amperes in a direction <u>opposite</u> to the electric field, which increases with the field. This phenomenon is effected by light and is decreased by the presence of potassium vapor.

4. The conductivity in potassium vapor when one electrode is potassium has been measured for temperatures up to 150°.

5. The conductivity in caesium vapor when one electrode is caesium has been measured for temperatures up to 100°.

6. Woodrow's observations on the emission of positive particles from alkali metals have been confirmed and for temperatures above 50° found to be large compared to the electron current.

7. The ratio between the number of electrons given off per second and the number of atoms present has been found for a given source of light to be $\dfrac{1}{5.88\times10^{10}}$.

8. At 150° light has practically no effect on the emission of electrons from potassium.

9. By comparing the currents for different temperatures in tube # 2, with potassium electrode, it is found that the greatest relative effect of light on the emission of electrons is at 25°

10. The maximum vapor pressure possible for potassium at 25° has been found to be 0.0587 mm.

The author wishes to express his indebtedness to Professor A.P. Carman and the Department of Physics for the facilities for this investigation, and to Professor Jakob Kunz who suggested the problem and has given many valuable suggestions.

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A.M. " " " 1903

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Positions - Instructor , Park College, 1902-03

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Professor of Natural Science, Albany College, Oregon 1905 - 07

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Published paper in Physical Review, Jan. 1912, "Effect of Frequency on Capacity of Condenser with Kerosene for the Dielectric".